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Atomic, Crystal, Elastic, Thermal, Nuclear, and Other Properties of Beryllium

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ATOMIC, CRYSTAL, ELASTIC, THERMAL, NUCLEAR, AND OTHER PROPERTIES OF BERYLLIUM

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One of a Series of Reports on Beryllium

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Introduction

This report is part of a series of documents that provide a background to those involved in the construction of beryllium components and their applications. Topics on beryllium that have been or will be presented in this series are the following:

I General Background
II Atomic, Crystal, Elastic, Thermal, Nuclear, and other Properties of Beryllium
III Extraction
IV Purification and Casting of Ingots
V Beryllium Powders
VI Consolidation and Grades of Beryllium
VII Mechanical Properties of Beryllium and the Factors Affecting these Properties
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These reports will be combined as a handbook on beryllium. In the handbook, the subject of this report, "Atomic, Crystal, Elastic, Thermal, Nuclear, and other Properties of Beryllium" is identified as Section II with the prefix II being maintained for the sub-sections, figures, and tables. Accordingly, the same identification system is also used in this report. To date, in addition to this report, the reports on "Mechanical Properties of Beryllium and the Factors Affecting these Properties," "Consolidation and Grades of Beryllium," "Corrosion and Corrosion Protection of Beryllium," and "Joining of Beryllium" have been published. The second report (VI) includes room-temperature mechanical properties of the different beryllium grades.

The present report is divided into five sub-sections: Atomic/Crystal Structure, Elastic Properties, Thermal Properties, Nuclear Properties, and Miscellaneous Properties. In searching through different sources for the various properties to be included in this report, inconsistencies were at times observed between these sources. In such cases, the values reported by the Handbook of Chemistry and Physics[1] was usually used. In equations, except where indicated otherwise, temperature (T) is in degrees Kelvin.

II-1—Atomic/Crystal Structure

Beryllium normally exists in the close-packed hexagonal crystalline form, referred to as α-beryllium, in contrast to β-beryllium, the body-centered cubic form that is stable between 1250^{o}C and its melting point of 1287^{o}C. Some characteristics of beryllium related to the beryllium atom and crystal are listed in Table II-1-1. In the un-ionized state, beryllium has four electrons, $1s^2$ and $2s^2$. The orbital radii are 0.143 and 1.19 Å for the 1s and 2s electrons, respectively.[2] The first and second ionization potentials are 9.320 and 18.206 eV. The valence is 2. The variation of the two lattice parameters (a- and c-axes) of α-beryllium with temperature is given in Table II-1-2.[2] Note that the c/a ratio decreases as the crystal (lattice) expands with increasing temperature.

A plot of the change in the crystal-lattice parameters with temperature is shown in Fig. II-1-1.

Table II-1-1. Atomic/Crystal Structure/Characteristic of Beryllium.[1, 3-5]

Atomic number	4
Atomic radius	1.125 Å
Atomic volume	4.96 cm^3/g-atom
Atomic weight	9.01218 g
Density	1.8477 g/cm^3 (Commercial grades in range of 1.82 to 1.85 g/cm^3)
Electronic structure	$1s^2 2s^2$
Crystal structure < 1250°C	Hexagonal close-packed (α Be)
Crystal structure > 1250°C	Body-centered cubic (β Be)
Lattice constants	a = 2.286 Å; c = 3.583 Å; c/a = 1.568; ideal = 1.633

The density of beryllium between room temperature and1227°C is given by the following expression:[6]

$$(g/cm^3) = 1.823 - 6.933 \times 10^{-5} T - 1.513 \times 10^{-8} T^2 \text{ (T in } ^oC)$$

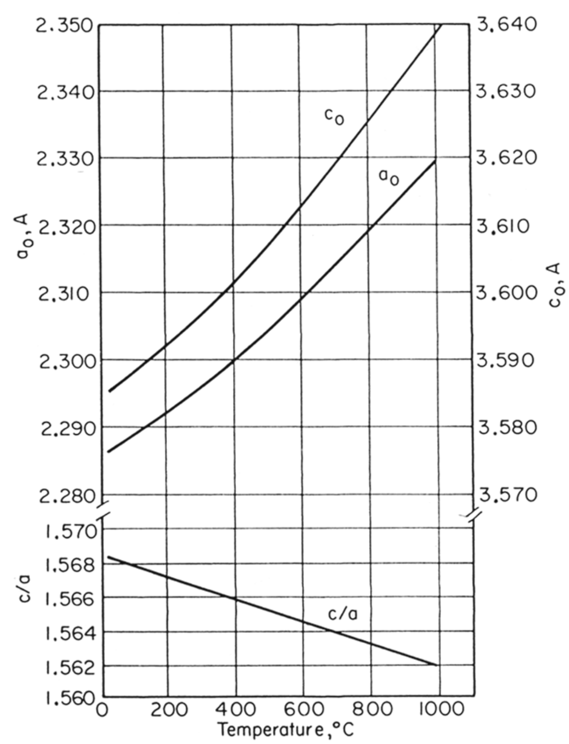

Fig. II-1-1. The effect of temperature on the lattice parameters of beryllium.[7]

Table II-1-2. Variation of Lattice Parameters with Temperature.[2]			
°C	a-axis	c-axis	c/a
50	2.287	3.585	1.5679
100	2.288	3.587	1.5676
200	2.292	3.591	1.5670
300	2.296	3.596	1.5664
400	2.300	3.601	1.5658
500	2.304	3.607	1.5652
600	2.309	3.613	1.5646
800	2.319	3.625	1.5633
1000	2.330	3.639	1.5620

II-2—Elastic Properties

The elastic properties can be given either as a tensorial (matrix) representation or in terms of engineering constants. The elastic properties in the tensorial representation are defined by the stiffness (c_{ij}) and compliance (s_{ij}) matrices and individually referred to as elastic constants. The engineering elastic constants are Young's modulus (E), shear modulus (G), Poisson's ratio (ν), bulk modulus (β), and compressibility (κ). Some variability is reported in elastic properties values, especially for Poisson's ratio. This can be attributed to the anisotropy of beryllium. Because of the anisotropic crystalline properties of the hexagonal beryllium crystal and the preferred orientation (texture) of the polycrystalline material, these properties should be related to the corresponding crystallographic axis. Unfortunately, this is not always done. The elastic properties at room temperature are listed in Table II-2-1.

Table II-2-1. Elastic Properties of Beryllium at Room Temperature.[1, 4, 5, 8]	
Elastic constants (10^{11} Pa)	c_{11} = 2.923; c_{12}=0.267; c_{13} = 0.140; c_{33} = 3.364; c_{44} =1.625
Young' modulus	3.03 x 10^5 Mpa [(2.87-3.21)10^5 Mpa]
Shear modulus	1.35 x 10^5 Mpa
Bulk modulus	1.10 x 10^5 Mpa
Poisson's ratio	0.01 to 0.08
Isothermal compressibility	0.0883 x 10^{-10} m^2/N[a]
Adiabatic compressibility	0.103 x 10^{-10} m^2/N
[a]Stress/(change in volume)/(unit volume) = stress	

Young's modulus as a function of crystallographic orientation for a single crystal of beryllium is shown in Fig. II-2-1.[8] Young's modulus as a function of temperature for various grades of beryllium is shown in Fig. II-2-2[6] and that for two hot-pressed beryllium grades, S-200E and S-65B are shown in Fig. II-2-3.[9] At room temperature, Young's modulus is unaffected by strain rate. Above about 425°C (797°F), it increases with increasing strain rate. This is illustrated in Fig. II-2-4, which also includes the change in dynamic modulus with temperature.[8] The differences between the static and dynamic values are explained in terms of thermodynamics involving the difference between specific heats at constant pressure and at constant volume as well as being attributed to creep at the elevated temperatures. The dynamic Young's modulus of elasticity of beryllium for two different orientations as a function of temperature is shown in Fig. II-2-5.[8] The change in modulus with temperature below 25°C is shown in Fig. II-2-6.[8] The grades and histories of the metals for Figs. II-2-5 and II-2-6 were not given.[a]

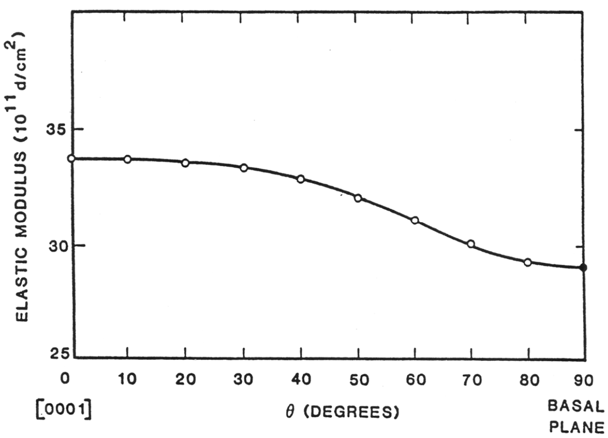

Fig. II-2-1. Young's modulus of a single crystal of beryllium as a function of the crystallographic orientation in a plane normal to the basal plane.[8]

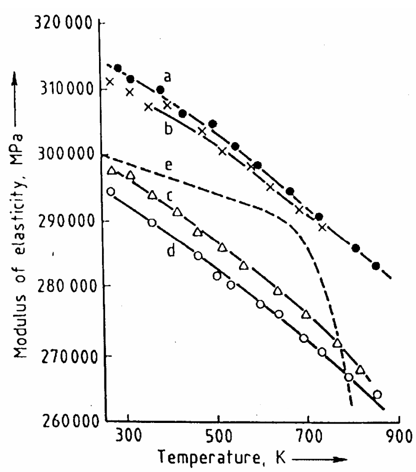

Fig. 2-2. Young's modulus of various grades of beryllium as a function of temperature: a) pressure sintered, b) cast and cross rolled, c) cast and extruded, d) powder metallurgy and extruded, e) pressure sintered (1 wt.% BeO).[6]

[a] Reference 8 is a report consisting of an extensive review of elastic properties; it does not include any original work. Inconsistencies between different figures may be due, at least to some extent, to results from different investigators.

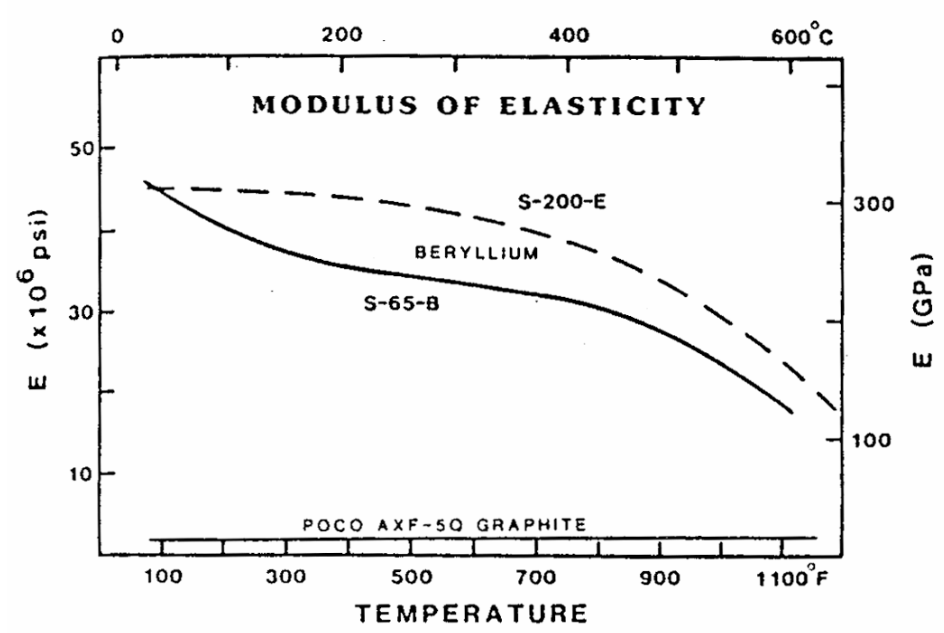

Fig. II-2-3. Young's modulus as a function of temperature for smooth-bar specimens from VHP blocks of S-65B and S-200E beryllium. Included are results of a competing graphite product.[9]

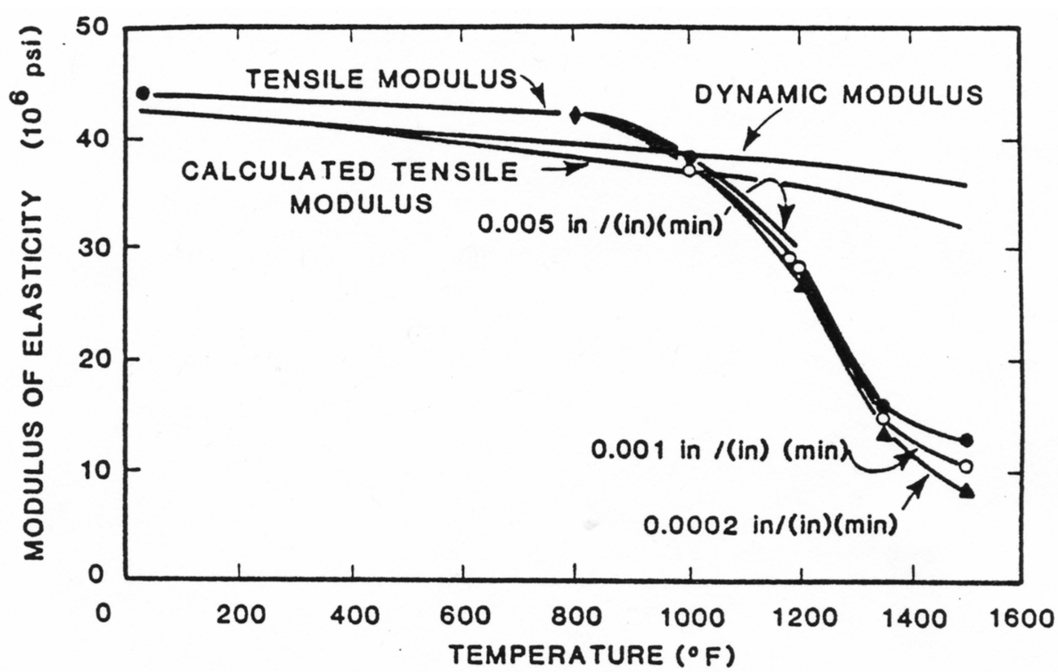

Fig. II-2-4. Comparison of dynamic modulus with static modulus of QMV Beryllium between room temperature and 1500°F (815°C).[8]

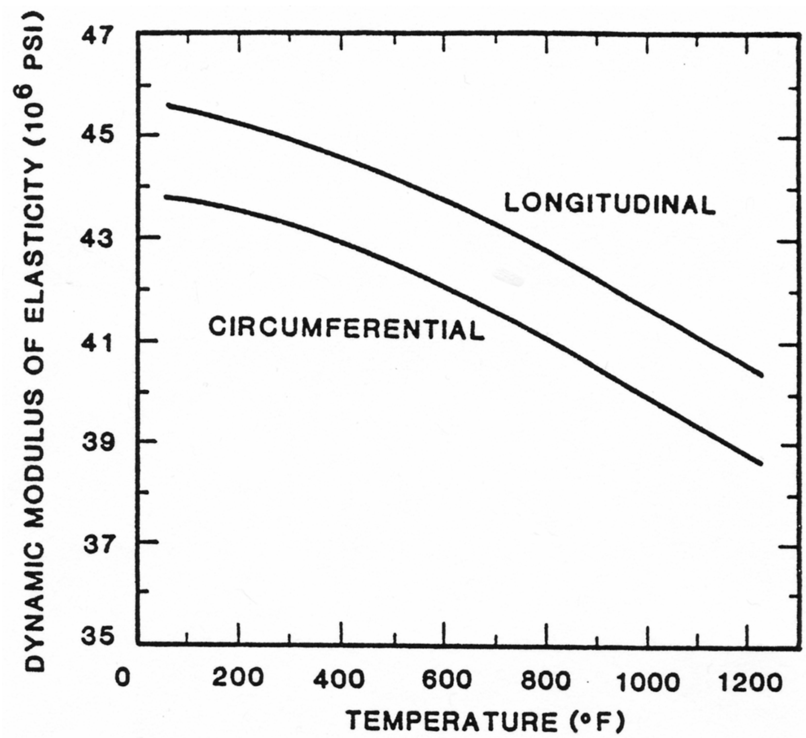

Fig. II-2-5. Dynamic Young's modulus between room temperature and 1200°F (649°C) for two different orientations of a beryllium sample.[8]

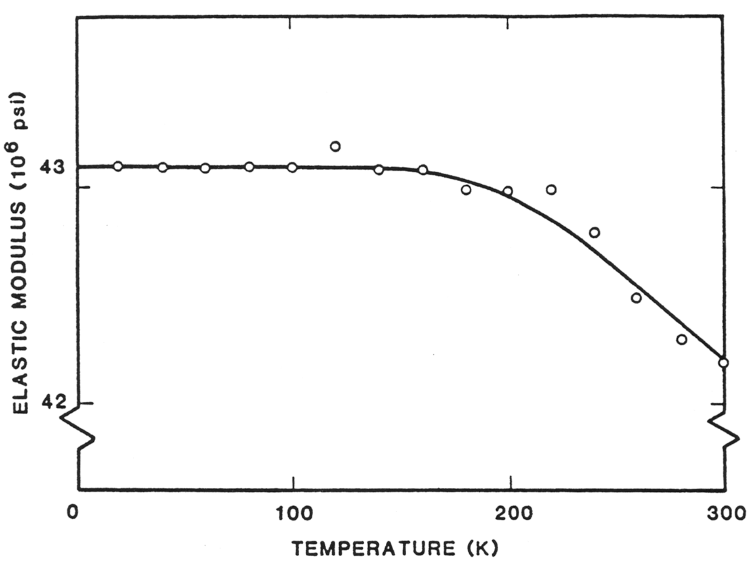

Fig. II-2-6. Dynamic Young's modulus as a function of temperature below 300K (27°C).[8]

Precision elastic limit (P. E. L.), 0.01% offset yield strength, and Young's modulus for the S-200F material are listed in Table II-2-2. The P. E. L. determination followed the MAB specification method.[I] Young's modulus was obtained according to ASTM E-111. The P. E. L. is the stress required to produce a permanent strain of 10^{-6}; it is also known as the microyield stress.

Table II-2-2. Tensile Elastic Limits and Yield Strength at Room Temperature for VHP S-200F Beryllium.[10]			
Orientation	P. E. L., MPa	Yield strength, 0.01% offset, MPa	Young's modulus, GPa
Longitudinal	32.4	190	3.11 ± .07
Transverse	34.5	203	3.10 ± .05

The elastic properties are affected by porosity. Young's modulus (E) for a wide variety of as-fabricated beryllium, containing less than 0.3 volume fraction of porosity and at temperatures below1000°C, can be represented to within ± 15% by:

$$E\ (\text{MPa}) = 3.00 \times 10^{5}\ e^{-4.574p}[1-2.016 \times 10^{-4}(T-293)],$$

where p is the volume fraction of porosity and T is the temperature in degrees K.[11] The ultimate tensile strength for VHP S-200 beryllium can similarly be represented to within ±10% by:

$$\text{UTS (MPa)} = 324\ e^{-4.733p}[1-1.925 \times 10^{-4}(T-293)-1.750 \times 10^{-6}(T-293)^{2}+9.198 \times 10^{-10}(T-293)^{3}].$$

The shear modulus and Poisson's ratio as a function of temperature for a cross-rolled cast beryllium are shown in Fig. II-2-7.[6] The shear modulus and Poisson's ratio of beryllium as a function of temperature below 300K (27°C) are shown in Figs. II-2-8 and II-2-9, respectively.[8]

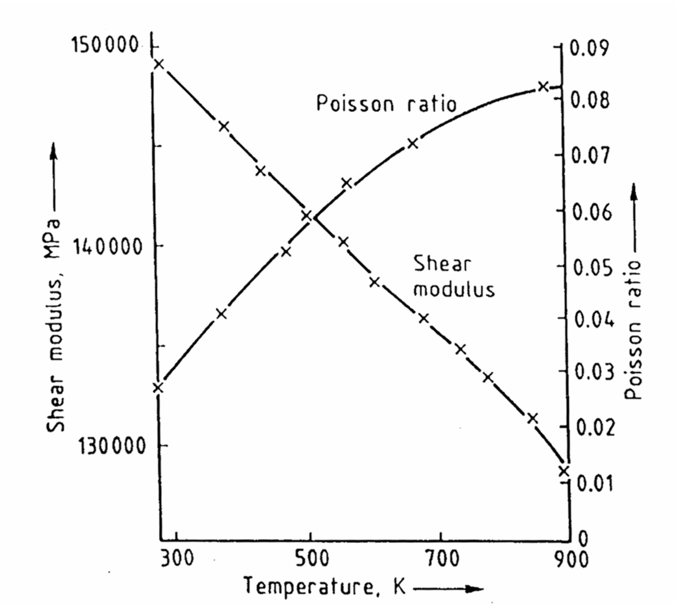

Fig. II-2-7. Shear modulus and Poisson's ratio of cross-rolled cast beryllium as a function of temperature.[6]

Inconsistencies can be seen between the values at 300K in Fig. II-2-7 compared to those in Figs. II-2-8 and II-2-9, namely, 148 GPa versus 141 GPa for the shear modulus and 0.027 versus 0.01 for Poisson's ratio. Such differences are probably due to material composition, processing history, and sample orientation. The room-temperature shear properties for VHP S-200F reported for torsion tests are listed in Table II-2-3.[10] The shear values close to 300 K are given as 134 GPa.

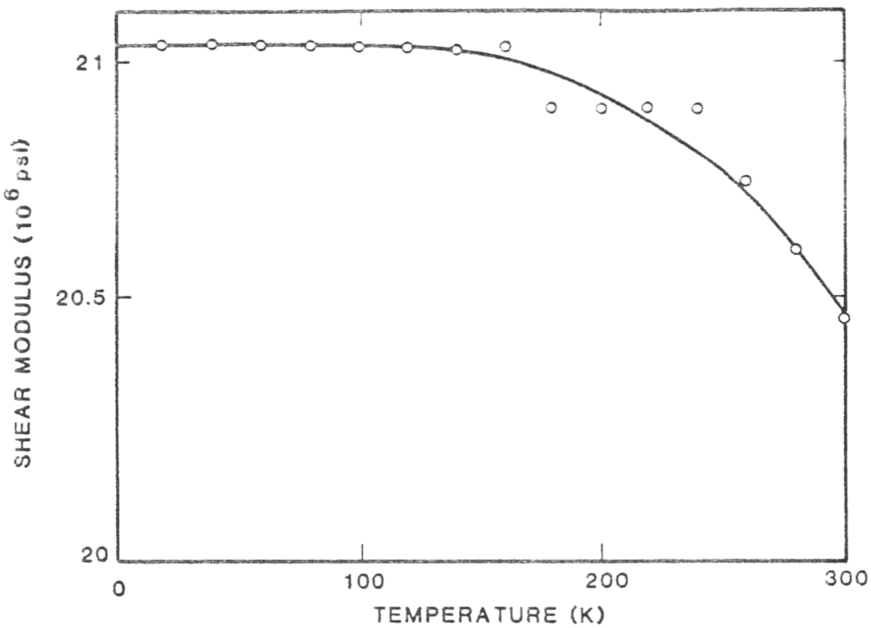

Fig. II-2-8. Shear modulus for beryllium between 0 and 300K.[8]

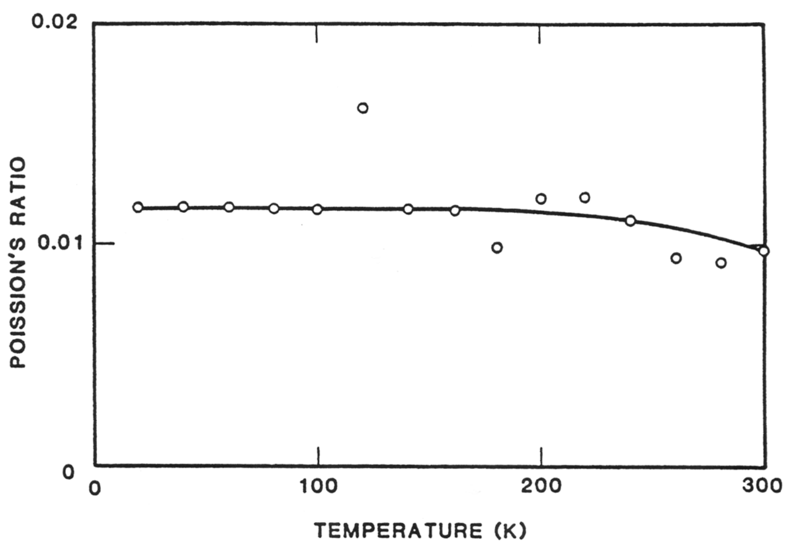

Fig. II-2-9. Poisson's ratio for beryllium between 0 K and 300 K.[9]

A number of elastic properties reported for VHP S-200E are listed in TableII-2-4.[12] Tests were performed in the pressing direction and in two orthogonal directions perpendicular to the pressing direction. The measured values indicated that there was little anisotropy in the pressed

Table II-2-3. Shear Properties of VHP S-200F Obtained from Torsion Tests at Room Temperature.[10]		
Orientation	Shear modulus, GPa	Shear rupture modulus, MPa
Longitudinal.	134 ± 5	297 ± 12
Transverse	134 ± 3	309 ± 8

beryllium; however, the calculated values (Lamé's parameter[a] and Poisson's ratio) showed significant differences. The elastic stiffness constants from six different published sources were compared to illustrate the variable results obtained for beryllium.[12] These data are tabulated in Table II-2-5. Table II-2-6 compares results obtained for compliance constants from four published sources. Table II-2-7 lists Poisson's-ratio values calculated for six different compliance directions.

Table II-2-4 Elastic Properties of VHP S-200E Beryllium.[8]		
Property	Pressing direction (Z)	Average of transverse (X & Y) directions
Dilatational wave velocity, mm/µsec	12.84 ± 0.04	12.57 ± 0.1
Shear-wave velocity, mm/µsec	8.86 ± 0.04	8.82 ± 0.1
Shear modulus, MPa	1.453×10^5	1.440×10^5
Bulk modulus, MPa	1.114×10^5	1.005×10^5
Young's modulus, MPa	3.038×10^5	2.923×10^5
Lamé's parameter	145.6	44.8
Poisson's ratio	0.046	0.015

Fig. II-2-10 shows the shear modulus as a function of temperature calculated from experimental data of Young's modulus for three different values of Poison's ratio.[8] Averaging published data from 14 different sources, gave a value of 0.0476, which was suggested as the most probable value for Poisson's ratio. The shear modulus as a function of temperature for three different values of Poisson's ratio is shown in Fig. II-2-11. The compressibility, which is the reciprocal of the bulk modulus, is shown in Fig. II-2-12 as a function of temperature.[8]

Assuming isotropic properties, the shear modulus (G) can be calculated from Young's modulus (E) and Poison's ratio (ν) using the relationship:

$$E = 2G\,(1 + \nu).$$

[a] Lamé's parameter, λ, is defined as: $\lambda = \nu E/(1+\nu)(1-2\nu)$, where ν is Poisson's ratio.

Table II-2-5. Beryllium Stiffness Constants at Room Temperature Reported by Six Different Sources.[8] $(10^{10}$ Pa)					
C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	C_{66}
29.23	2.67	1.40	33.64	16.25	13.28
30.8	-5.8	8.7	35.7	1.0	17.5
29.54	2.59	-0.10	35.61	17.06	13.48
30.87	2.16	1.05	34.25	15.54	14.04
29.39	2.69	1.4	33.78	16.33	13.35
29.2	2.4	0.6	34.9	16.3	13.4
29.65	2.50	0.87	34.44	16.30	13.51
The bottom row consists of averages (of five rows) excluding the second row. The author excluded this row since its values differed considerably from the other reported values. C_{66} is calculated by: $C_{66} = 1/2\ (C_{11} - C_{12})$; C_{66} is calculated by: $C_{66} = 1/2\ (C_{11} - C_{12})$.					

Table II-2-6. Beryllium Compliance Constants at Room Temperature Reported by Four Different Sources.[8] $(10^{-11}$ $Pa^{-1})$					
S_{11}	S_{12}	S_{13}	S_{33}	S_{44}	S_{66}
0.341	-0.0299	0.001	0.2808	0.5862	0.7420
0.35	-0.03	-0.01	0.30	0.61	0.76
0.326	-0.023	-0.009	0.292	0.644	0.712
0.345	-0.028	-0.005	0.287	0.616	0.746
0.341	-0.0.028	-0.006	0.290	0.614	0.740
The bottom row consists of averages of the prior four rows. S_{66} is calculated by: $S_{66} = 2\ (S_{11} - S_{12})$.					

Table II-2-7. Poisson's Ratio (ν) for Different Directions in Beryllium Single Crystals.[8]	
$\nu_{12} = E_{100} \times S_{12} = 0.07$	$\nu_{31} = E_{001} \times S_{13} = 0.03$
$\nu_{21} = E_{101} \times S_{12} = 0.07$	$\nu_{23} = E_{010} \times S_{23} = 0.03$
$\nu_{13} = E_{100} \times S_{13} = 0.03$	$\nu_{32} = E_{001} \times S_{23} = 0.03$

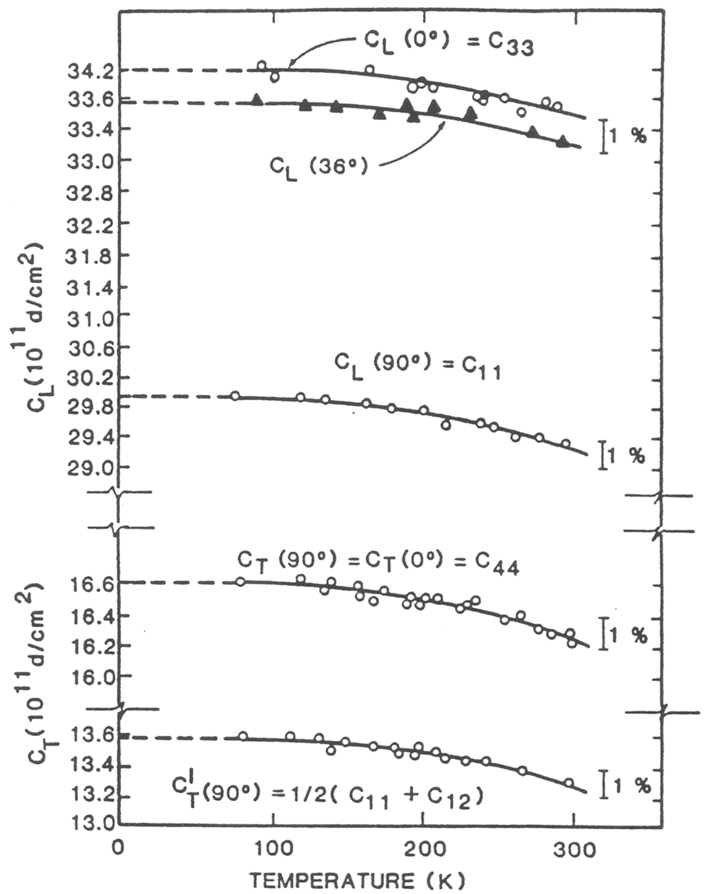

Fig. II-2-10. Shear modulus as a function of temperature calculated from experimental Young's-modulus values for different values of Poisson's ratio.[8]

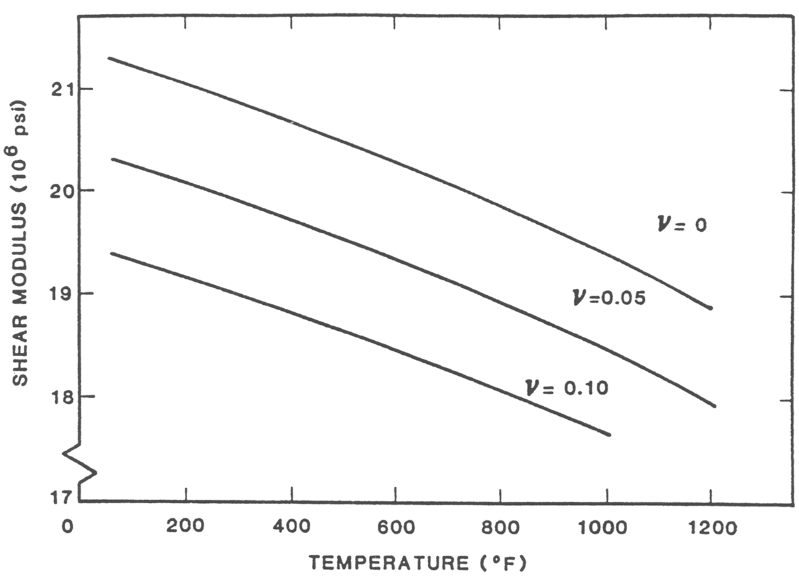

Fig. II-2-11. Shear modulus of beryllium as a function of temperature for three different values of Poisson's ratio.[8]

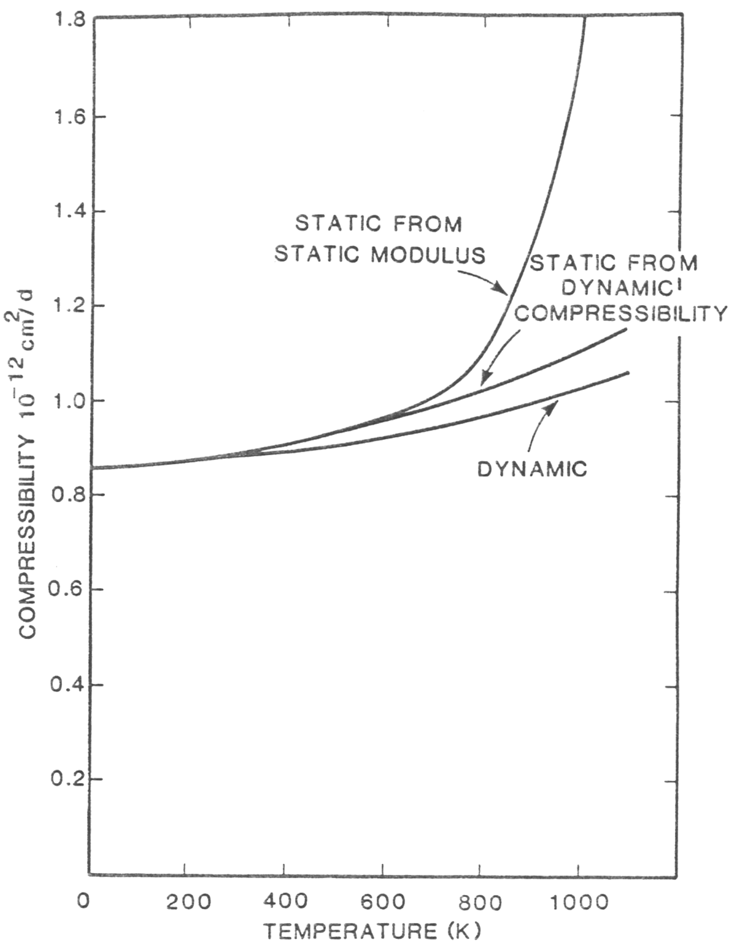

Fig. II-2-12. Typical compressibility curves for beryllium as a function of temperature.[8]

II-3—Thermal Properties

Some room-temperature thermal properties of beryllium are listed in Table II-3-1. Results of several thermal-property measurements of grade S-65-B beryllium are listed in Table II-3-2.[9]

The mean coefficient of thermal expansion from room temperature to 900°C is shown in Fig. II-3-1.[13] The average coefficient of thermal-expansion values for VHP S-200E and S-200F over the range of 5 to 65°C (278 to 338 K) for the longitudinal and two transverse directions are listed in Table II-3-3.[10] The author points out that measurements were made on only one sample of each material.[10] Table II-3-4 lists the change in length relative to the length at 20°C and the coefficient of thermal expansion over a range of temperatures from -268 to -27°C (5 to 300 K) for HIP beryllium. The specimens were manufactured by Brush Wellman from material designated as "0-50 HIP." Average coefficients of thermal expansion of beryllium over temperature ranges from 25 to 100°C up to 25 to 1000°C are listed in Table II-3-5.[4] The coefficients of thermal expansion of beryllium single crystals at low temperatures, perpendicular and parallel to the c-axis, are reported in Table II-3-6.[2, 14]

Table II-3-1. Some Room-Temperature Thermal Properties of Beryllium.[1, 3-5, 15]	
Melting point	1287°C
Latent heat of fusion	1.89 (1.89 to 2.92) kcal/g-atom
Boiling point (760Torr)	2471°C
Heat of sublimation	75.56 (75.5 to 78.8) kcal/g-atom
Heat of evaporation	53.55 (53.5-74.1) kcal/g-atom
Specific heat (25°C, constant pressure)	3.92 cal/g-atom/^{o}C
Enthalpy at 25°C	465 cal/g-atom
Heat of transformation (α to β)	1.80 cal/g-atom
Entropy (25^{o}C)	2.28 cal/g-atom
Thermal conductivity	216 W/m/^{o}C
Thermal diffusivity (room temperature)	0.18 m^2/h
Temperature coefficient of linear expansion	11.3 x 10^{-6}/^{o}C (0-50^{o}C)
Temperature coefficient of resistivity	0.025 $\Delta\rho/\rho_o$/^{o}C
Contraction on solidification	3%

Table II-3-2. Some Thermal-Property Measurements of Grade S-65-B Beryllium covering a Range of Temperatures.[9]

Temperature, ^{o}C (K)	Thermal conductivity, W/cm^{o}C	Heat capacity, cal/g^{o}C	Thermal diffusivity, cm^2/s	Density, g/cm^3
51 (324K)	1.873	0.455	0.540	1.820
139 (412K)	1.523	0.535	0.376	1.814
183 (456K)	1.438	0.560	0.339	1.808
242 (415K)	1.338	0.583	0.304	1.806
291 (564K)	1.288	0.604	0.283	1.801
336 (609K)	1.252	0.624	0.267	1.797
400 (673K)	1.166	0.637	0.244	1.791
464 (737K)	1.104	0.653	0.225	1.785
543 (816K)	1.018	0.664	0.206	1.777
619 (892K)	0.961	0.683	0.190	1.769
700 (973K)	0.884	0.702	0.171	1.760
854 (1127K)	0.758[a]	0.737[a]	0.141	1.742
996 (1269K)	0.638[a]	0.769[a]	0.115	1.725

[a] Extrapolated value

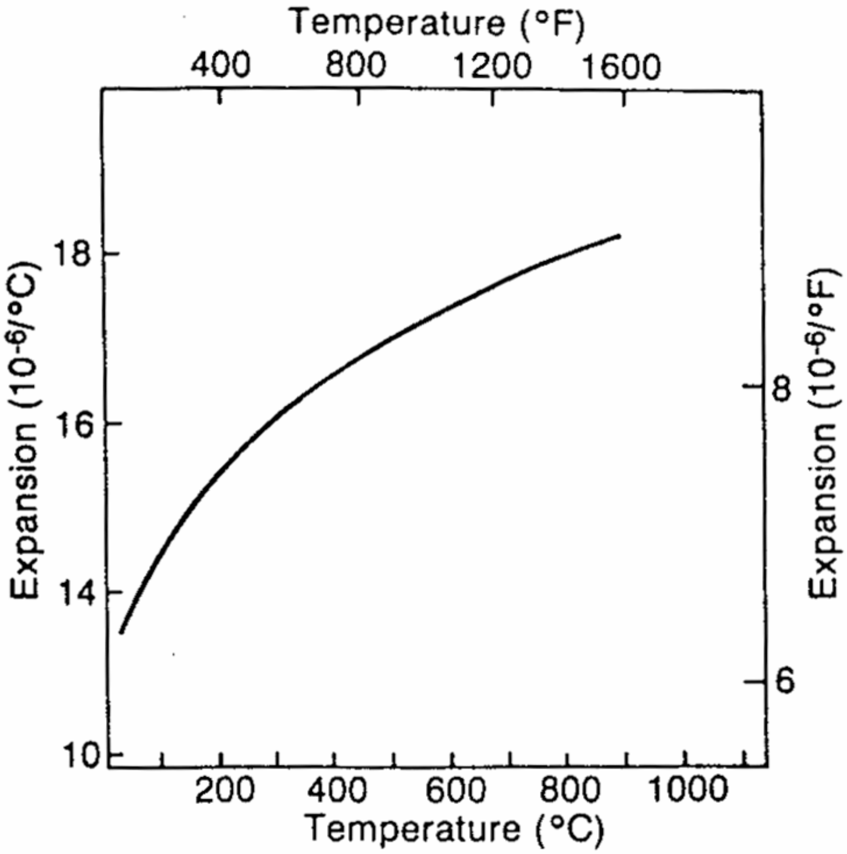

Fig. II-3-1. Mean coefficient of thermal expansion from room temperature to indicated temperature of normal-purity beryllium block and sheet.[13]

Table II-3-3 Average Coefficient of Thermal Expansion (α) for Vacuum-HotPressed S-200E and S-200F from 5 to 65°C.[10]		
Direction	S-200E α ($10^{-6}/^{o}C$)	S-200F α ($10^{-6}/^{o}C$)
Longitudinal	11.39	11.39
Transverse-1	11.57	11.76
Transverse-2	11.45	11.82

Table II-3-4. Coefficient of Thermal Expansion (α) and Length Change Relative to 293.16 K for HIP Beryllium Metal[16]					
T (^oK)	α (K^{-1})	$\Delta L/L^{293}$ (10^{-6})	T (K)	α (K^{-1})	$\Delta L/L_{293}$ (10^{-6})
0	0.00	–1298	110	1.77×10^{-6}	–1254
5	3.16×10^{-10}	–1298	120	2.27	–1234
10	9.60	–1298	130	2.82	–1209
15	2.31×10^{-9}	–1298	140	3.41	–1178
20	4.83	–1298	150	4.01	–1140
25	9.14	–1298	160	4.62	–1097
30	1.61×10^{-8}	–1298	170	5.24	–1048
35	4.83	–1298	180	5.84	–993
40	4.24	–1298	190	6.43	-931
45	6.48	–1298	200	7.00	–864
50	9.61	–1297	210	7.54	–791
55	1.38×10^{-7}	–1297	220	8.07	–713
60	1.94	–1296	230	8.57	–630
65	2.66	–1295	240	9.04	–542
70	3.56	–1293	250	9.50	–449
75	4.67	–1292	260	9.94	–352
80	5.99	–1289	270	1.04×10^{-5}	–251
85	7.52	–1286	273.16	1.05	–218
90	9.26	–1281	280	1.08	–145
95	1.12×10^{-6}	–1276	290	1.11	–35
100	1.32	–1270	293.16	1.13	0
105	1.54	-1263	300	1.15	+78

Table. **II-3-5. Average Coefficients of Thermal Expansion of Beryllium for Several Ranges of Temperature.**[4]	
Temperature range, ^oC	Average coefficient of expansion (10^{-6})
25 to 100	11.6
25 to 300	14.5
25 to 600	16.5
25 to 1000	18.4

Low-temperature results of the thermal expansion relative to 300 K and the coefficient of thermal expansion are shown in Figs. II-3-2 and II-3-3, respectively, for VHP S-200F beryllium. Only one sample was used that had been machined, stress relieved at 788^oC for one hour, final machined, etched to remove any machine damage, nickel plated, and finally polished to a 1/4-wavelength finish.[17] The thermal expansion results reported for HIP'ed beryllium made using impact-ground powder is shown in Fig. II-3-4. The process was evaluated in its use for large precision mirrors (space applications) where anisotropy cannot be tolerated.[11]

Table**. II-3-6. Coefficients of Thermal Expansion of Beryllium Single Crystals at Low Temperatures.**[2, 14]			
Temp., ^{o}K	Perpendicular to c-axis (10^{-6})	Parallel to c-axis (10^{-6})	Volume coefficient (10^{-6})
273 to 270	10.6	7.7	29.0
265 to 260	10.2	7.3	27.6
255 to 250	9.5	6.9	26.0
250 to 245	9.2	6.7	25.1
240 to 235	8.5	6.3	23.4
230 to 225	7.9	5.9	21.7
225 to 220	7.6	5.7	20.9
220 to 215	7.3	5.5	20.1
210 to 205	6.7	5.0	18.3
200 to 195	6.1	4.6	16.9
190 to 185	5.6	4.1	15.2
180 to 175	5.0	3.6	13.5
175 to 170	4.7	3.3	12.7
165 to 160	4.1	2.7	10.9
160 to 155	3.8	2.5	10.1
150 to 145	3.2	1.9	8.3
140 to 135	2.7	1.5	6.8
130 to 125	2.1	1.0	5.3
125 to 120	1.9	0.9	4.6
115 to 110	1.3	0.5	3.2
105 to 100	0.9	0.3	2.1
100 to 95	0.7	0.2	1.6
95 to 90	0.6	0.1	1.3
85 to 80	0.4	---	0.8

Figure II-3-5 compares the thermal linear expansion between a polycrystalline beryllium and that of a single beryllium crystal in directions parallel to the a-axis and c-axis, respectively. The curves are based on the equations shown in Table II-3-7.[18] Figure II-3-6 shows expansion-versus temperature curves recommended for polycrystalline beryllium and single crystals of beryllium. The curves are based on data obtained from 38 sources.[18] Figure II-3-7 compares the average degree of anisotropy of thermal expansion for beryllium of essentially constant chemical composition for a structural grade beryllium (indicated as “comp A”) produced by five different fabrication techniques.[19] Also included is an instrument-grade hot-pressed beryllium having a high oxide content and a very fine grain size (indicated as “comp B”).[20] The results are based on two specimens per material with 12 determinations on each specimens. The authors state that the thermal expansion results are consistent with the degree of preferred orientation that was observed.

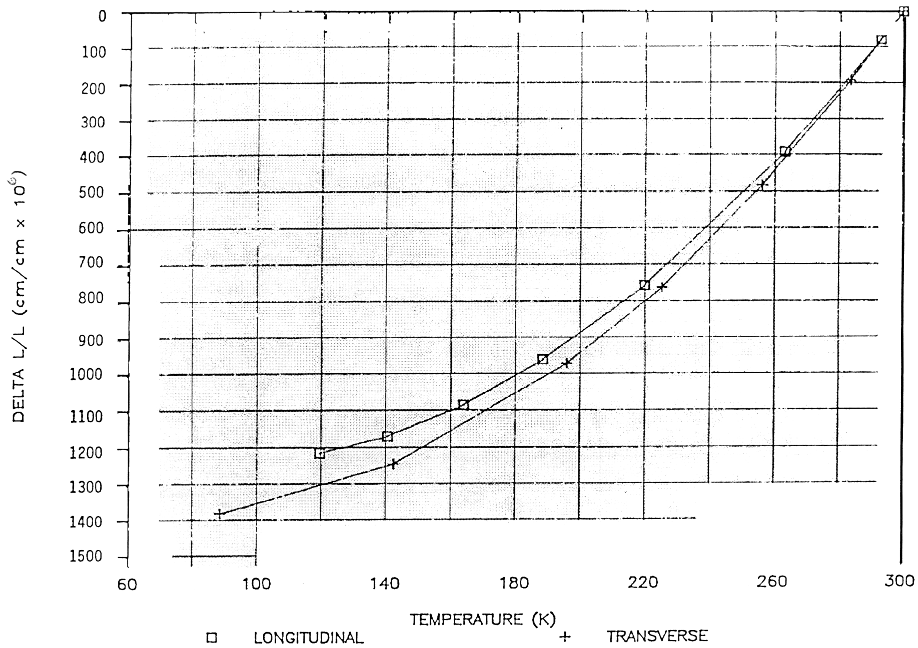

Fig. II-3-2 Low temperature thermal expansion, $\Delta L/L_{300\ K}$, for VHP S-200F relative to 300K (27^{o}C).[17]

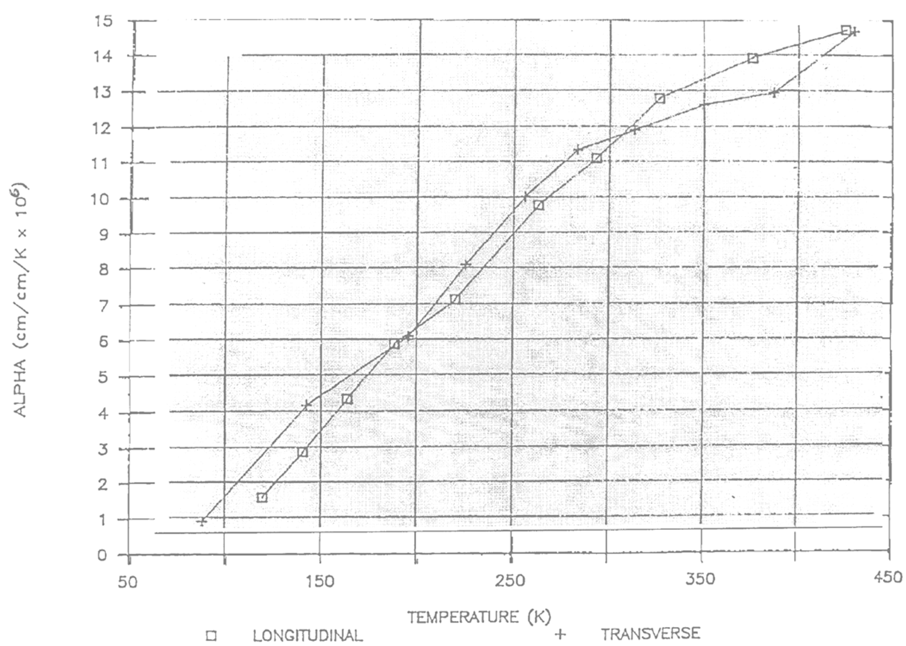

Fig. II-3-3 Coefficient of thermal expansion of beryllium versus temperature for VHP S-200F.[17]

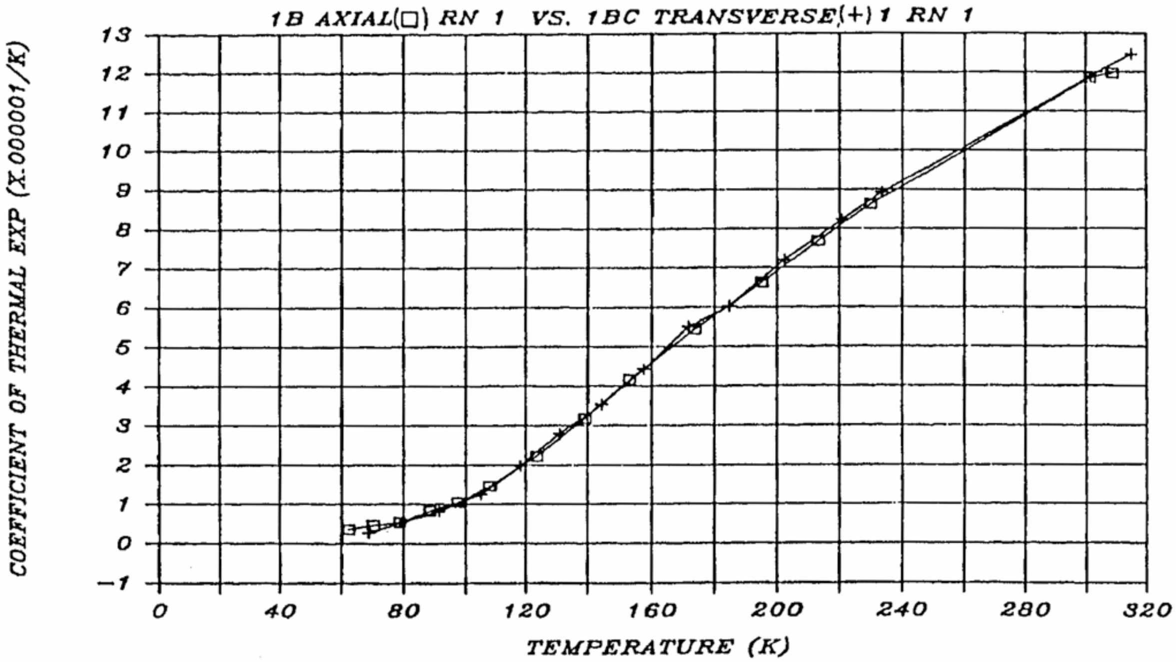

Fig. II-3-4. Coefficient of thermal expansion of a beryllium cube in two orthogonal directions showing excellent isotropy. The cube was HIP'd beryllium using impact-ground powder.[11]

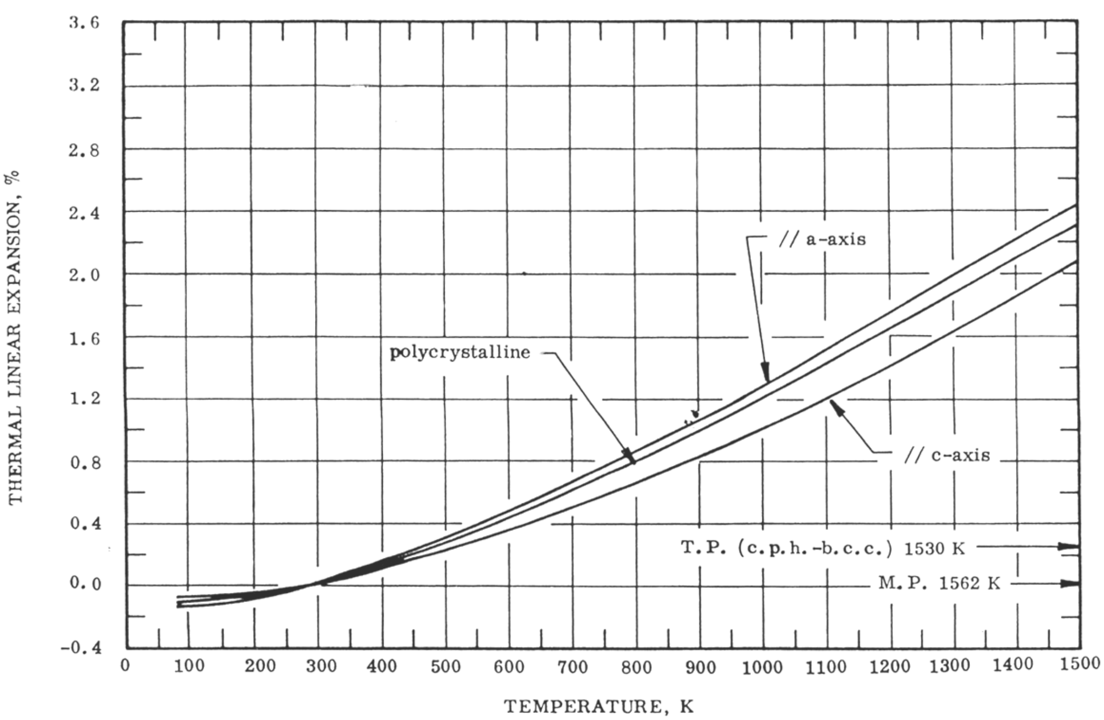

Fig. II-3-5. Thermal linear expansion relative to 293 K of polycrystalline beryllium and of a beryllium single-crystal parallel to the a-axis and c-axis, respectively.[18]

TABLE II-3-7 EQUATIONS for CURVES SHOWN in FIGURE II-3-5[18]		
Orientation/ type	Thermal linear expansion, $(L - L_0)/L_0$	Temperature range, K
ll a-axis Single crystal	$1.242 \times 10^{-3}\,(T\text{-}293) + 1.144 \times 10^{-6}\,(T\text{-}293)^2 - 4.567 \times 10^{-10}\,(T\text{-}293)^3$	293 to 895
ll a-axis Single crystal	$1.063 + 2.123 \times 10^{-3}\,(T\text{-}895) + 3.197 \times 10^{-7}\,(T\text{-}895)^2 - 1.373 \times 10^{-10}\,(T\text{-}895)^3$	895 to 1500
ll c-axis Single crystal	$9.881 \times 10^{-4}\,(T\text{-}293) + 5.475 \times 10^{-7}\,(T\text{-}293)^2 + 7.916 \times 10^{-11}\,(T\text{-}293)^3$	293 to 895
ll c-axis Single crystal	$0.809 + 1.733 \times 10^{-3}\,(T\text{-}895) + 6.904 \times 10^{-7}\,(T\text{-}895)^2 - 1.519 \times 10^{-10}\,(T\text{-}895)^3$	895 to 1500
Polycrystalline	$1.148 \times 10^{-3}\,(T\text{-}293) + 9.724 \times 10^{-7}\,(T\text{-}293)^2 - 2.978 \times 10^{-10}\,(T\text{-}293)^3$	293 to 895
Polycrystalline	$0.978 + 1.995 \times 10^{-3}\,(T\text{-}895) + 4.346 \times 10^{-7}\,(T\text{-}895)^2 - 1.307 \times 10^{-10}\,(T\text{-}895)^3$	895 to 1500

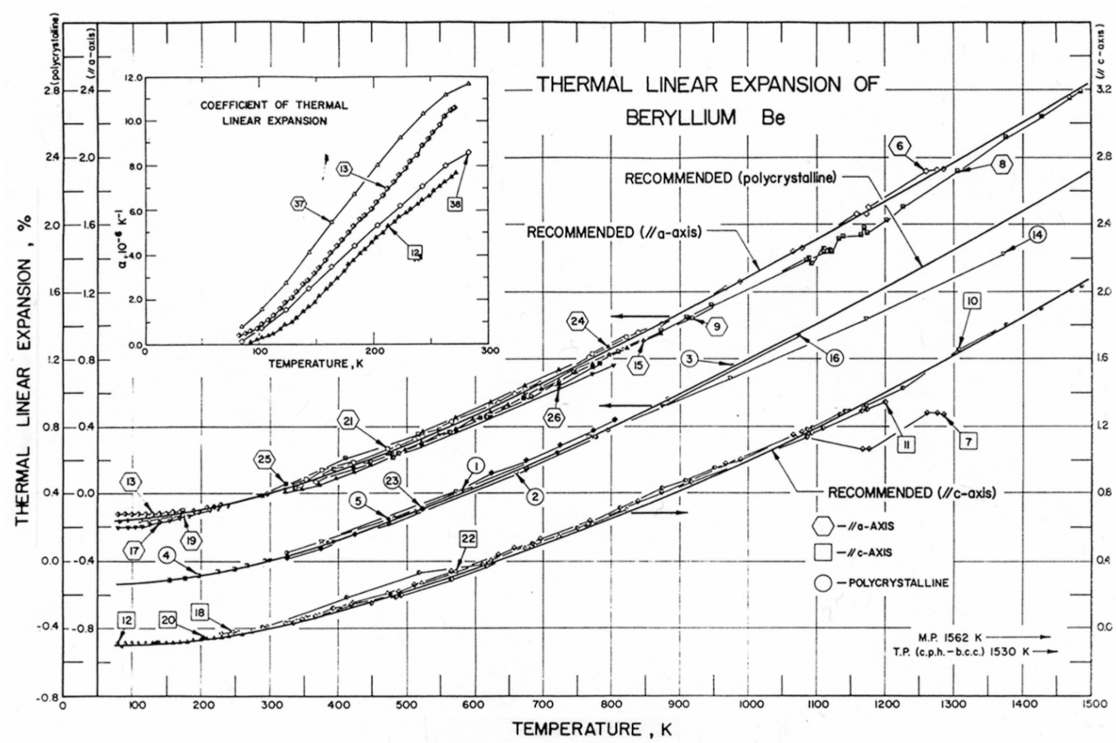

Fig. II-3-6 Recommended thermal linear expansion curves for beryllium based on a large number (38) of investigations. The vertical axes from left to right are for polycrystalline material and for single crystals parallel to a-axis and c-axis, respectively. Details on the temperature ranges, the materials evaluated, and the original references are presented in the current reference.[18]

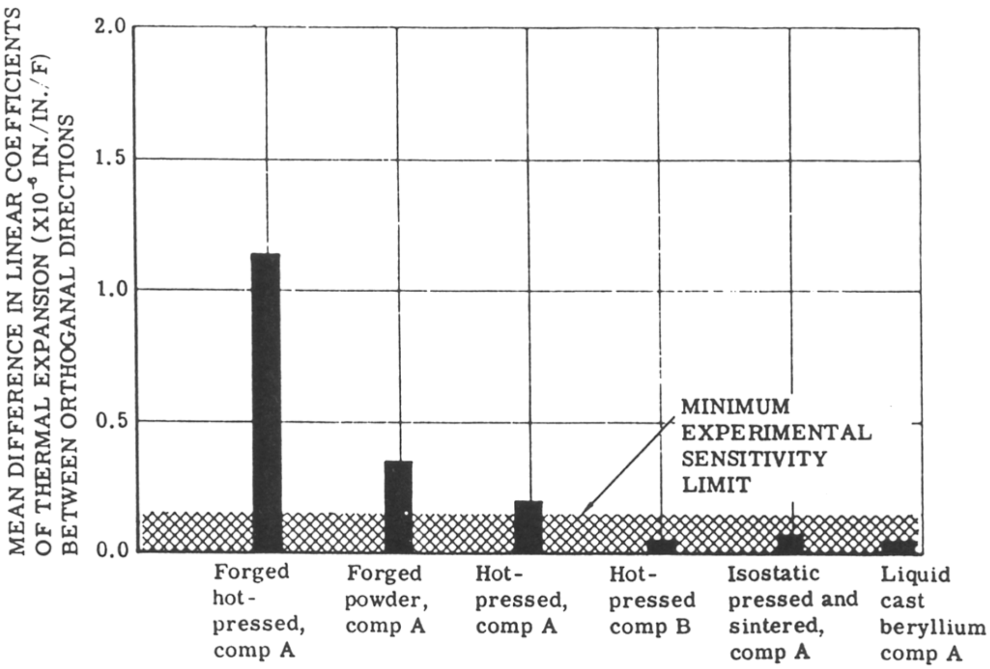

Fig. II-3-7 Comparison of the degree of thermal expansion anisotropy for beryllium fabricated by several techniques: A—2% maximum BeO, B—4% minimum BeO.[20]

The temperature coefficients for unrelaxed thermal microstresses[b] that were calculated for beryllium are listed in Table II-3-8 together with values reported for other HCP polycrystalline materials.[21], The authors suggest that in beryllium the residual stresses may greatly influence cracking in textured materials, for example, in rolled or extruded plate.

Table II-3-8 Temperature Coefficient of Thermal Microstresses in HCP Polycrystals.[21]

Material	$\sigma_{11}/\Delta T$, 10^2 Mpa	$\sigma_{33}/\Delta T$, 10^2 Mpa	$\tau_{max}/\Delta T$, 10^2 Mpa	$\sigma_{max}/\Delta T$, 10^2 Mpa
Cd	2.8	-21	2.5	6.3
Zn	4.9	-3.7	4.3	12.2
Mg	0.17	-0.34	0.26	0.67
Be	-0.74	1.55	-1.14	-2.3
BeO	-0.635	1.27	-0.95	-2.3

The thermal expansion relative to 298K (25^{o}C) of beryllium, having 100-percent density, in the range of 298 to 1500 K (25 to 1227^{o}C) is given as:[11]

$$\Delta l/l_{298} = 8.43 \times 10^{-4}(1+1.36 \times 10^{-3}T-3.53 \times 10^{-7}T^2)(T-298).$$

[b] Anisotropic dimensional changes occur during heating or cooling of hexagonal close-packed metals. In polycrystalline materials, microstrains and corresponding microstresses are developed by the mutual restrictions of adjacent grains to these dimensional changes.

The mean coefficient of thermal expansion for a near-isotropic S-65B beryllium over the temperature range from 20 to 1200°C is given as:[6]

$$\alpha\,(10^{-6}K^{-1}) = 11.0388 + 1.0859 \times 10^{-2}T - 4.4735 \times 10^{-6}T^2 + 8.6305 \times 10^{-10}T^3.$$

In both expressions, T is temperature in degrees K.

A study on thermal expansion and dimensional stability that was performed on several different beryllium histories showed that cast, hot-pressed, and isopressed forms were found to have nearly isotropic expansion properties. By contrast, the difference between anisotropic and isotropic thermal expansion ranged from 0.09 x 10^{-6}/°C for hot-pressed beryllium to 2.07 x 10^{-6}/°C for heavily forged beryllium. The average value for the hot-pressed material was 11.5 x 10^{-6}/°C.[20] For isotropic sintered blocks such as S-65, differences in thermal expansion in different directions are small (not more than a few percent); for heavily deformed grades differences in thermal expansion could exceed 20 percent.[6]

Both the specific heat and thermal conductivity of beryllium are claimed to be relatively insensitive to fabrication method, low levels of impurity, and, to a certain extent, radiation in a neutron environment above room temperature.[6] Small levels of impurities and displacement damage have little effect on thermal conductivity.[11] However, the presence of as-fabricated porosity and/or helium bubbles can cause a large reduction in the effective thermal conductivity. The following expression is claimed to be a relatively good fit to data of both vacuum-hot-pressed and foam (low-density) beryllium for porosities up to 50%:[11]

$$k_{eff} = (1-p)(1+3.7p^2)^{-1}k_o,$$

where k_{eff} is the effective thermal conductivity, p is the volume fraction of porosity, and k_o is the thermal conductivity for virtually zero porosity. Plasma-sprayed beryllium shows a significantly lower value than that predicted by this expression. The thermal conductivity of a normally dense beryllium over the temperature range from 27 t0 550°C is given as:[11]

$$k_o = 291(1 - 1.650 \times 10^{-3}T + 1.464 \times 10^{-6}T^2 - 5.125 \times 10^{-10}T^3)\,W/m/^oC$$

A number of expressions reported for the specific heat at constant pressure (C_p) of beryllium are presented here. The temperature range for the first expression was not given. The next two expressions cover the range between room temperature and 1283°C; the fourth between 327 and 1287°C; the fifth between 1287 and 1927°C (As previously indicated, throughout this report, except where noted, T refers to degrees K):

$$C_p = 4.54 + 2.12 \times 10^{-3}T - 0.82 \times 10^5T^{-2}\ cal/^oC/g\text{-}atom,$$ [5]

$$C_p = 5.238 + 13.378 \times 10^{-4}T - 15.31 \times 10^4T^{-2}\ cal/^oC/g\text{-}atom,$$ [11]

$C_p = 3.752 + 7.185 \times 10^{-3}T - 6.704 \times 10^{-6}T^2 + 2.746 \times 10^{-9}T^3$ cal/°C/g-atom,[6]

$C_p = 4.322 + 2.18 \times 10^{-3}T$ cal/°C/g-atom,[2] and

$C_p = 6.079 + 5.138 \times 10^{-4}T$ cal/°C/g-atom.[2]

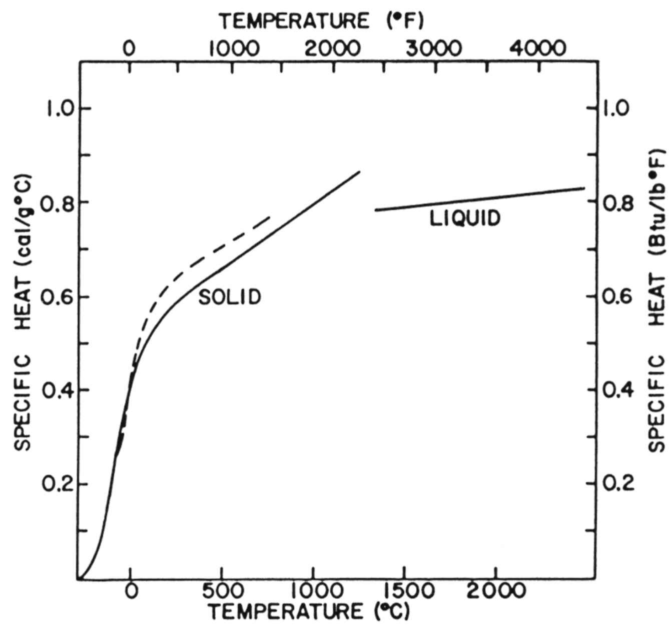

Fig. II-3-8. Specific heat of beryllium as a function of temperature. Results from two different sources. Dashed line is for a brake grade of normal-purity block.[13]

The specific heat as a function of temperature covering both solid and liquid beryllium is shown in Fig. II-3-8.[13] A plot of specific heat as a function of temperature is also shown in Fig. II-3-9.[7] The plot consists of data reported for nine different investigations and shows excellent agreement between these various studies. Some low-temperature results reported for specific heat and enthalpy are shown in Table II-3-9.[2] Figures 10[22] and 11[23] show the specific heat as a function of temperature covering both solid and liquid regions, with the curve in Fig. 11 extending down below 40 K.

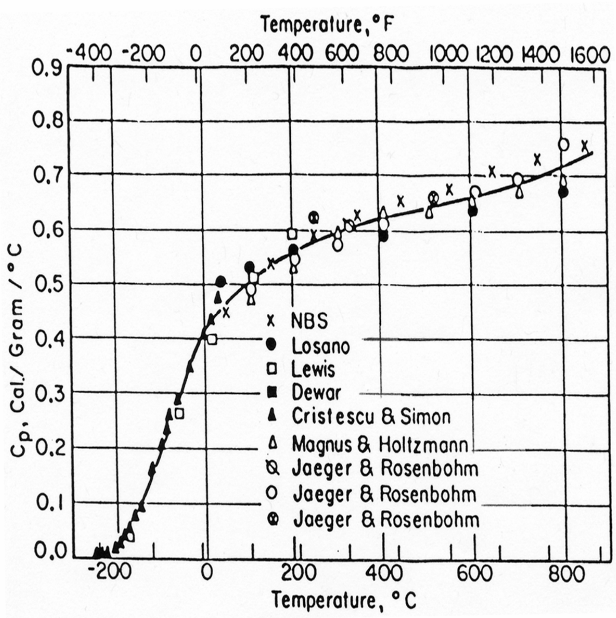

Fig. II-3-9 The specific heat of beryllium (per gram) as a function of temperature.[7]

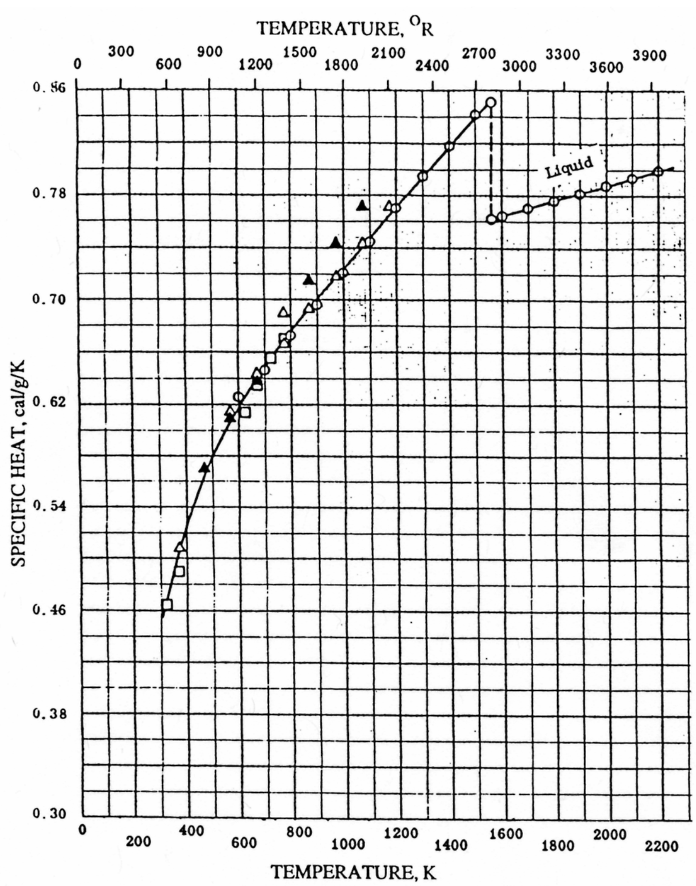

Fig. II-3-10. Specific heat of beryllium as a function of temperature from four different sources for both solid and liquid regions: O, —99□% Be; Δ, σ—99.5% Be.[22]

The thermal conductivity as a function of temperature for several different sources of beryllium is shown in Figs. II-3-12 [13] and II-3-13. [7] The thermal conductivity as a function of temperature of beryllium from six different sources plotted on the same graph is shown in Fig. II- 3-14.[22] The thermal conductivity as a function of temperature for well annealed high-purity beryllium over a wide range of temperatures (2 to 1000 K) is shown in Fig. 15. A peak value in the conductivity is seen at about 35 K (-238°C).

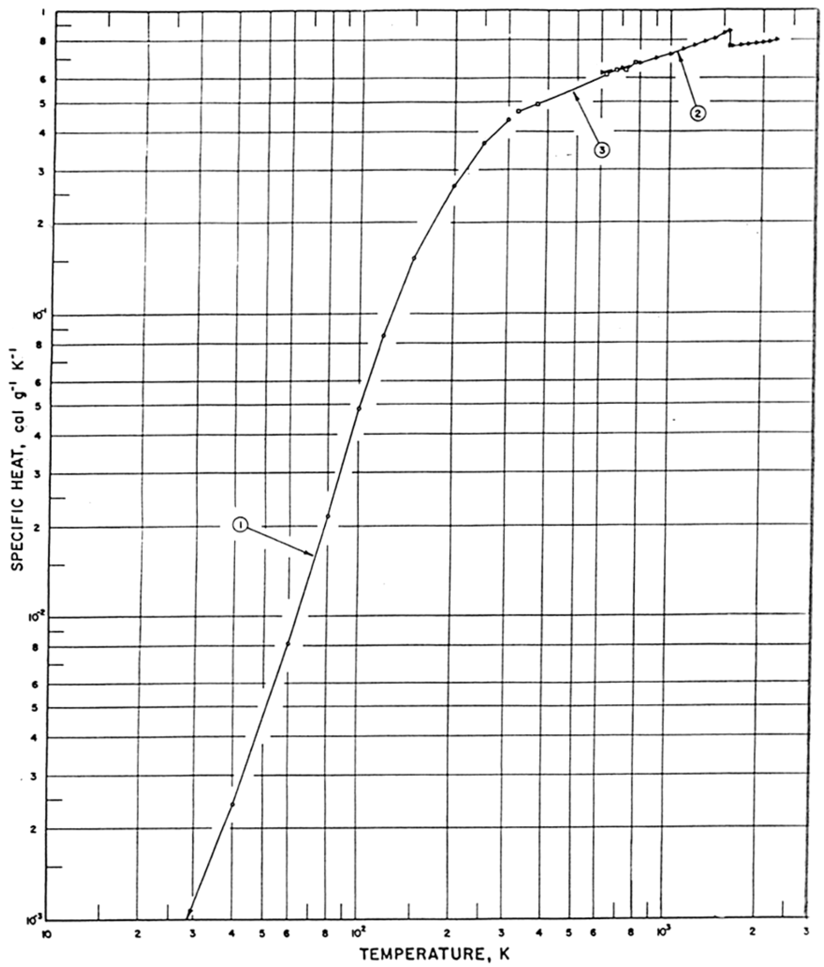

Fig. II-3-11 The specific heat of beryllium covering a wide temperature range, from 40 K up to 2200 K: 1—0 to 300 K, 99.5% Be, high-temp. extrusion of powder; 2—600 to 2200 K, 99.8% Be, pulverized and tightly filled into ampoules; 3—323 to773 K, 99.8% Be, history not given.[23]

Thermal diffusivity (m^2/h) as a function of temperature is shown in Fig. II- 3-16. The thermal diffusivity determines the rate of heat propagation by conduction. It can be calculated by the following expression:

$$\alpha = \lambda/\rho C_p,$$

where α is the thermal diffusivity, λ is the thermal conductivity, ρ is the density, and C_p is the specific heat.[13]

Table II-3-9. Specific Heat and Enthalpy at Low Temperatures.[2]					
Temp., ºK	C_p,cal/g/ºK	ΔH, cal/g	Temp.,ºK	C_p,cal/g/ºK	ΔH, cal/g
1	0.000006	0.000003	80	0.0217	0.404
3	0.000019	0.000028	100	0.0476	1.08
6	0.000043	0.000119	140	0.125	4.42
10	0.000093	0.00038	180	0.220	11.3
20	0.00038	0.0025	220	0.308	21.9
40	0.00238	0.026	260	0.392	36.1
60	0.0081	0.125	300	0.471	53.3

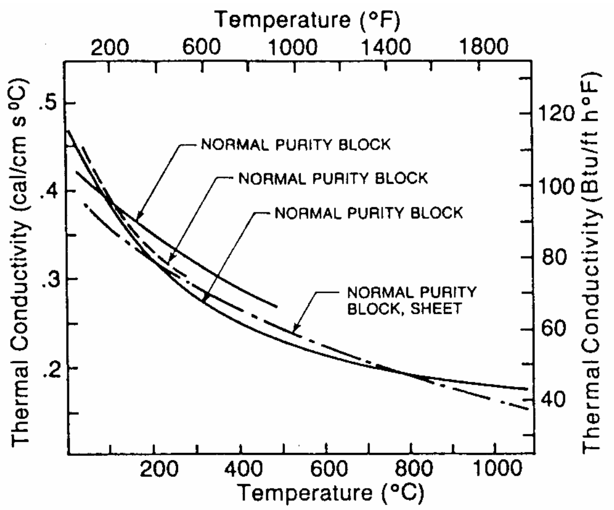

Fig.II-3-12 Thermal conductivity of normal-purity beryllium block and sheet as a function of temperature.[13]

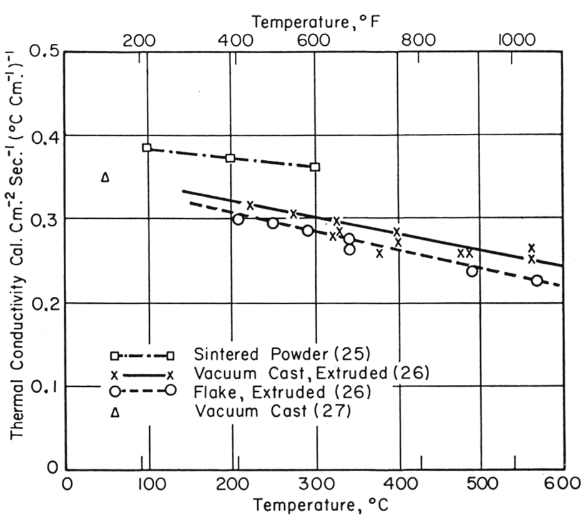

Fig. II-3-13. Thermal conductivity of several types of beryllium as a function of temperature.[7]

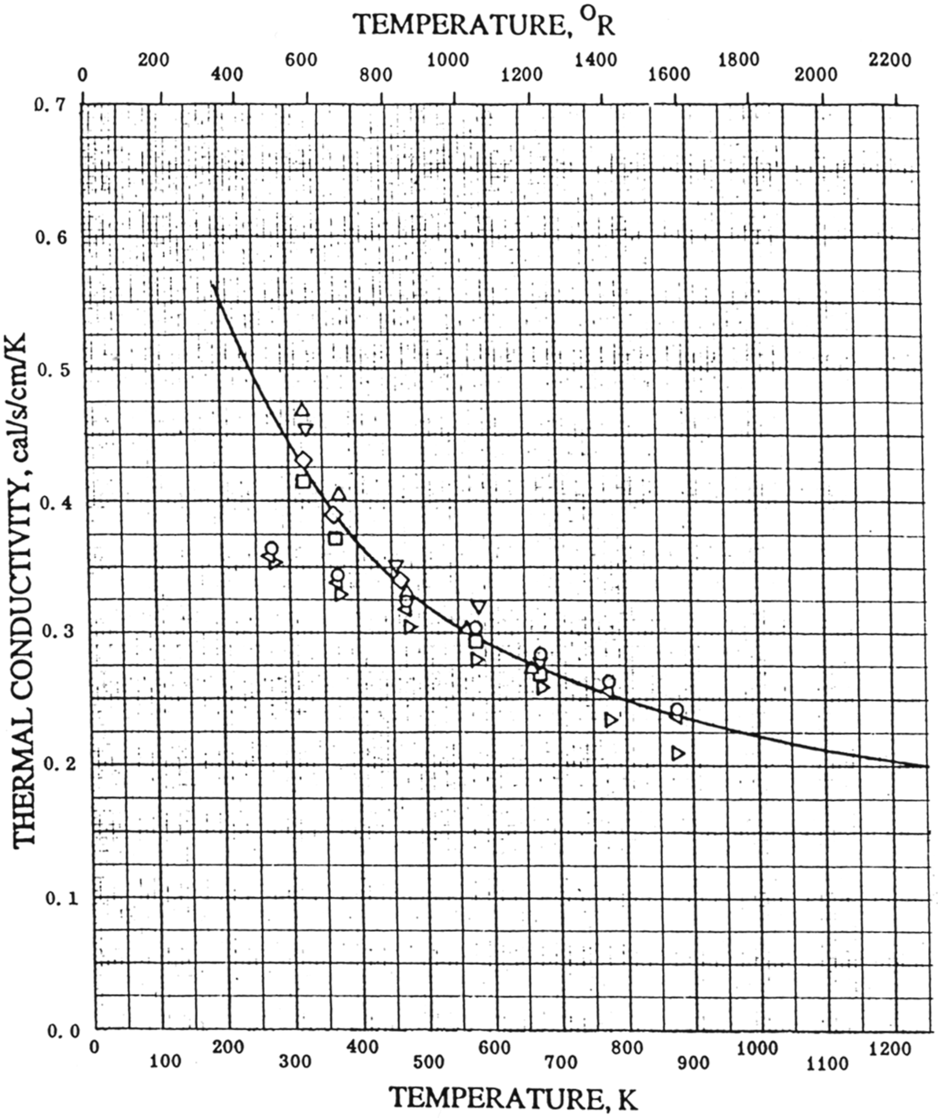

Fig. II-3-14. Thermal conductivity of beryllium as a function of temperature:—data from 322 to 672 K, listed as as-received condition with a density of 1.829 g/cm^3; Δ—322 to 672 K, as previous plus heat treated to above 700 ^{O}C; ◊—322 to 672 K, listed as as-received condition with a density of 1.865 g/cm^3; ∇—322 to 672 K, as previous plus heat treated to above 700 ^{O}C; O—273 to 875 K, no additional information; —273 to 875 K vacuum-cast and extruded pure Be; —273 to 875 K, flake, extruded pure Be.[22]

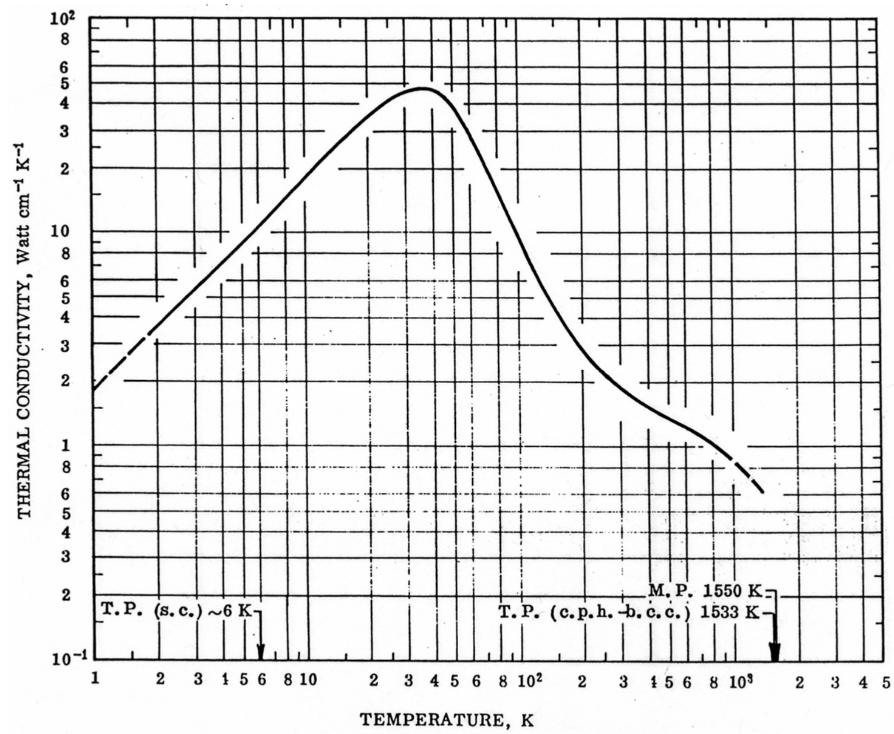

Fig. II-3-15. Thermal conductivity for well annealed high-purity beryllium showing a maximum in conductivity at about 360 K. Data is believed to be accurate to 5% near room temperature and from 5 to 15% at other temperatures.[25]

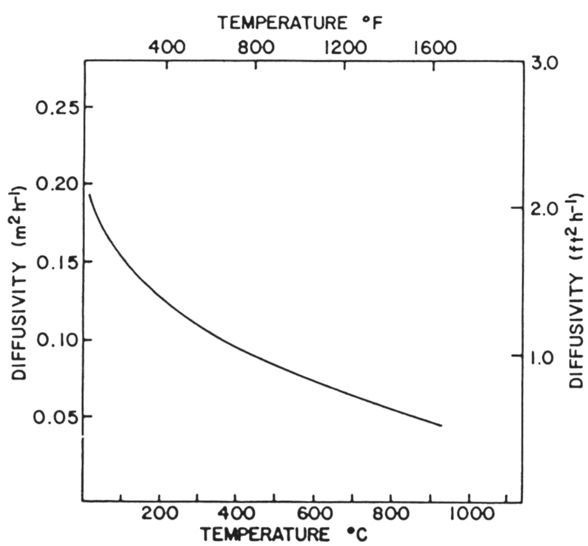

Fig. II-3-16 Thermal diffusivity of normal-purity block and instrument-grade block of beryllium.[13]

Thermal diffusivity as a function of temperature for well annealed high-purity beryllium is shown in Fig. II-3-17.[24]

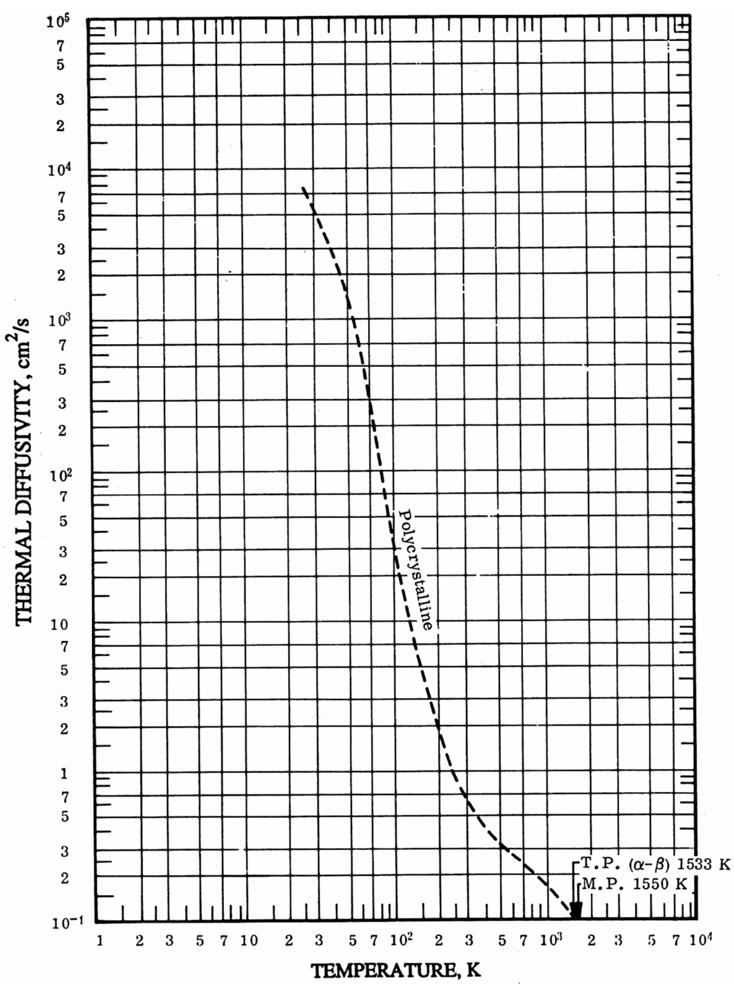

Fig. II-3-17. Thermal diffusivity as a function of temperature for well annealed high-purity beryllium. Uncertainty of ± 15% above room temperature and ± 25% below, where values are only applicable to beryllium having a residual electrical resistivity of 0.0135 μΩ cm.[24]

The self-diffusion in beryllium single crystals perpendicular to the basal plane over a series of temperatures are listed in Table II-3-10. A plot of D versus 1/RT yields a straight line with the following expression:[26]

$$D_{\perp} = 0.19 \times \exp(-38{,}600/RT),$$

where $D_{\perp}$ is the self diffusion perpendicular to the basal plane. In a different investigation the expressions for self diffusion of beryllium perpendicular and parallel (D_{11}) to the basal plane are given as:[27]

$$D_{\perp} = (0.62 \pm 0.15) \times \exp[(-39{,}400 \pm 700)/RT], \text{ and}$$

$$D_{11} = (0.52 \pm 0.15) \times \exp[(-37{,}600 \pm 700)/RT].$$

The authors note that the ratio $D_{11}/D_{\perp}$ is greater than 1. This is consistent with the ratio of c/a being less than c/a ideal for beryllium. The authors also discuss diffusion of iron and silver in beryllium.[27]

Table II-3-10 Diffusivities in Beryllium Single Crystals Perpendicular to the Basal Plane.[26]		
np., ^{O}C	D, cm^2/sec	1/T (K) x 10^4
553	1.3×10^{-11}	12.10
553	1.5×10^{-11}	12.10
607	4.3×10^{-11}	11.35
607	4.4×10^{-11}	11.35
703	5.1×10^{-10}	10.25
804	4.0×10^{-9}	9.27
804	4.8×10^{-9}	9.27
902	1.4×10^{-8}	8.50
1002	5.3×10^{-8}	7.85
1002	4.8×10^{-8}	7.85
1025	6.3×10^{-8}	7.70

The vapor pressure of beryllium as a function of reciprocal temperature between 900 and 1283°C is shown in Fig. II-3-18 for three different beryllium processes,[7] and in Fig. II-3-19 [22] for two different beryllium compositions. Both figures cover about the same temperature range (900 to 1283°C). The vapor pressure over this temperature region, which is in the range of 10^{-10} to 10^{2} Pa, is given by the following expression:[6]

$$\text{Log p (Pa)} = 11.192 + 1.45 \times 10^{-4}T - 1.6734 \times 10^{4}\, T^{-1}\ (T, K)$$

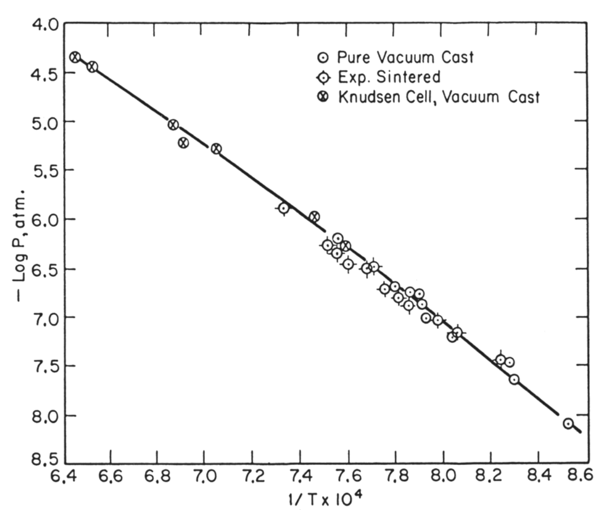

Fig. II-3-18 Vapor pressure of beryllium as a function of 1/T (^{O}K). [7]

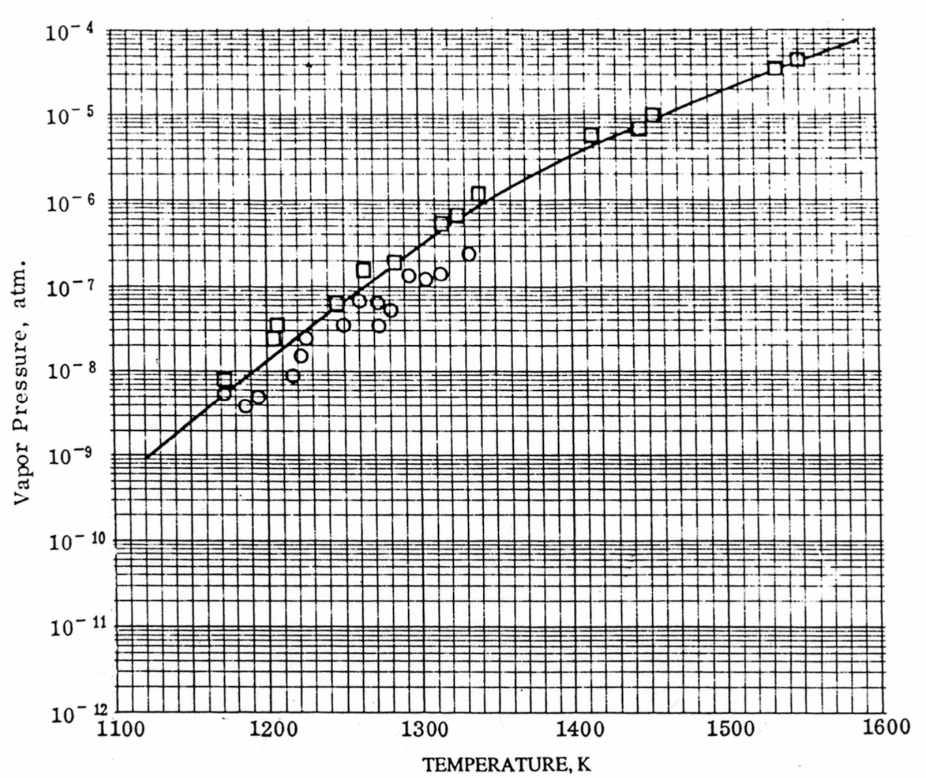

Fig. II-3-19. Vapor pressure of beryllium as a function of temperature:
O—1174 to 1336 K, 0.03 Fe. 0.022 Si, 0.008 Al, 0.004 Mg;
—□172 to 1552 K, vacuum cast, 0.14 Al, 0.Fe, 0.04 Si,
0.02 Mg, 0.01 each of Cr, Cu, Na, Ni, Zn.[22]

II-4—Nuclear Properties

Natural beryllium contains 100% of the ^{9}Be isotope. The principal isotopes of beryllium that have been identified are: ^{6}Be, ^{7}Be, ^{8}Be, ^{9}Be, and ^{10}Be.[5] Additional isotopes listed are: ^{11}Be, ^{12}Be, and ^{14}Be.[28] Some properties of the principal beryllium isotopes are listed in Table II-4-1 and II-4-2. In searching for data on beryllium isotopes, the published data could, in some cases, differ significantly. Irradiated beryllium yields gas-producing nuclear reactions. The major nuclear reactions are given in Table II-4-3. The nuclear reactions listed in Table II-4-3[5, 29] are calculated to produce about 2.2 to 2.6 cm^3 of gas per cm^3 of beryllium following a fluence of 10^{21} N/cm^2. The first of these reactions has a threshold of about 12 MeV. The second one has a threshold of 600 keV, as well as a strong resonance at 3 MeV.[29]

The beryllium atom has a reluctance to acquire additional neutrons while readily parting with one of its neutrons. It has a low neutron-capture cross-section (probability of capture) and a high neutron-scattering (large number of collisions with direction change and energy loss) cross section making the metal an excellent moderating material. Both of these cross-section areas[c] are dependent on the energy of the neutrons and the condition of the metal (e. g., impurities and grain size). The effect of impurities on the thermal neutron-capture (absorption) cross section is illustrated in Table II-4-4.[19] With these nuclear properties, beryllium is used as a neutron moderator in nuclear-chain reactions, as a source of neutrons, and as a window in X-ray tubes.

The (n, 2n) reaction with a high reaction cross-section, enables beryllium to function as a neutron multiplier. Beryllium is the leading neutron-multiplier candidate material for fusion applications. The combination of high neutron multiplication, low absorption, and high scattering characteristics provide excellent neutron thermalization. Therefore, beryllium can provide a high performance-breeding blanket for fusion systems.[5] The absorption cross section for thermal neutrons is 0.008 barns[d]; the scattering cross section for fast neutrons is 6 barns.[28] The resonance integral[e] is 0.004 barns. The mass-absorption coefficient for copper K-alpha radiation is 1.007 cm^2/g.[4]

The adsorption and desorption of deuterium have been measured on clean and on oxidized beryllium surfaces corresponding to the basal plane. The oxidized surfaces released all the adsorbed deuterium by about 177^oC. By contrast, for the clean surfaces, the desorption was not complete until the temperature was above 327^oC. The electron-affinity energy (difference between the ground state of the neutral atom and the lowest state of the corresponding negative ion) is indicated as being unstable for beryllium.[1]

Irradiated beryllium exhibits an increase in yield strength with a loss in ductility and a decrease in fracture toughness. Nil ductility is obtained when tested below 100^oC, whereas a small increase in yield strength with only a small decrease in ductility are obtained above 350^oC. Although the fracture toughness decreases with an increase of neutron fluence, the trend reverses at high fluences. It is suggested that all the beryllium grades exhibit approximately the same fracture toughness response to irradiation. At the lower temperatures, the helium atoms remain in the matrix; at the higher temperatures, the atoms diffuse and agglomerate causing swelling. As the fluence increases, the temperature required to produce complete annealing appears to increase and the temperature to produce 1% swelling decreases.[5].

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[c] The neutron cross section measures the probability of interaction of a neutron with matter. The cross section is visualized as a target area presented to the neutron by the nucleus. It is usually measured in units of barns (10^{-24} m^2 per atom). Absorption and scattering cross section refers to the capture and scattering of neutrons, respectively. The thermal-neutron absorption cross section is the sum of the cross sections of all reactions except that of the scattering cross section.

[d] A “barn” is a unit of 10^{-24} m^2/atom.

[e] Narrow peaks (at exceptionally high rates of reaction) in a plot of cross section versus energy are referred to as resonances. The resonance integral is the integral of the cross section as a function of neutron energy multiplied by the flux density.

Table II-4-1 Some Properties of Beryllium IsotopesL[30]			
Isotope	Half-life	Radiation, MeV	Source
^{6}Be	0.4 s ($3x10^{-21}$ s)[dn]	—	—
^{7}Be	53.5 days	γ	^{6}Li (d, n)
		0.453-0.485	^{7}Li (p, n)
			^{10}B (p, d)
			^{10}B (p, α)
			^{10}B (d, α, n)
^{8}Be	1.4 x 10^{-16} seconds	α	^{9}Be (γ, n)
		0.055	^{9}Be (n, 2n)
^{9}Be	Stable	—	—
^{10}Be	2.7 X 10^{6} years	β	^{9}Be (α, p)
		0.56-0.65	9Be (d, p)
			9Be (n, γ)
			^{10}Be (n, p)
			^{13}C (n, α)
Nuclear reactions of the stable isotope ^{9}Be: Gamma-ray bombardment $^{9}Be(\gamma, n)^{8}Be$ Neutron bombardment $^{9}Be(n, \alpha)^{6}He$ $^{9}Be(n, \gamma)^{10}Be$ $^{9}Be(n, 2n)^{8}Be$			

Table II-4-2 Some Additional Properties of Beryllium Isotopes[1]				
Isotope	Half life	Thermal-neutron cross section, barns	Resonance integral (RI), barns	Coherent scatter length (fm)[a]
^{7}Be	53.28 days	$\sigma_p = 3.9 \times 10^4$ b[b] $\sigma_a = 0.1$ b	$RI_p = 1.75 \times 10^4$ b	
^{9}Be	stable	8.8 mb	3.9 mb	7.79
^{10}Be	1.52 x 10^{6}years	<1.0 mb		
[a] (fm = 10^{-13} cm). [b] σ_p and σ_a proton and alpha production , respectively.				

The total neutron cross section of beryllium is a function of neutron energy and the grain size. This is illustrated in Fig. II-4-1, which shows the much greater transparency of the coarser-grained material in the lower energy range.[19] Apparently, there is no difference in the transparency at the higher energies. The figure depicts the behavior over the low-energy thermal range, where the neutrons are in thermal equilibrium with the moderator and where the cross section area increases with energy, and in the intermediate region, where the neutrons have been moderated but have not yet reached equilibrium. In the latter region, also known as the "slowing-down region", the cross section changes little with energy. In this range, the neutrons have wavelengths

Table II-4-3 Irradiated beryllium yielding gas-producing nuclear reactions[5]	
Irradiation source	Reaction
Fast neutrons	$Be^9 + n_f \rightarrow Li^7 + H^3$ $Be^9 + n_f \rightarrow Be^8 + 2n$ $Be^8 \rightarrow 2He^4$ $Be^9 + n_f \rightarrow He^6 + He^4$ $He^6 \xrightarrow{B-} Li^6$
Thermal neutrons	$Li^6 + n_t \rightarrow H^3 + He^4$

Table II-4-4 Effect of Various Impurities on the Thermal Neutron-Absorption Cross Section of Beryllium.[19]		
Impurity	Thermal neutron cross section, barns	Addition cross section to Be, mb
Boron	766	638
Cobalt	37.0	5.7
Manganese	13.2	2.2
Nickel	4.8	0.7
Iron	2.73	0.44
Calcium	0.44	0.10
Aluminum	0.24	0.08
Magnesium	0.07	0.03

comparable with the crystal lattice spacings and thus diffraction plays a role here with interactions occurring between incoming and scattered neutron wave fronts due to coherent scattering. For beryllium, a pronounced backward scattering occurs for neutrons having an energy of 0.00525 eV and a wave length of 3.96 Å, which is twice the longest lattice spacing of 1.98 Å for beryllium.[31] In the "fast region" (above about 1 eV), where the neutrons are produced by fission, the cross section decreases significantly with increasing energy. Other reactions, which may be similarly discussed, are nuclear reactions produced by gamma rays, alpha particles, deuterons, and protons.[31]

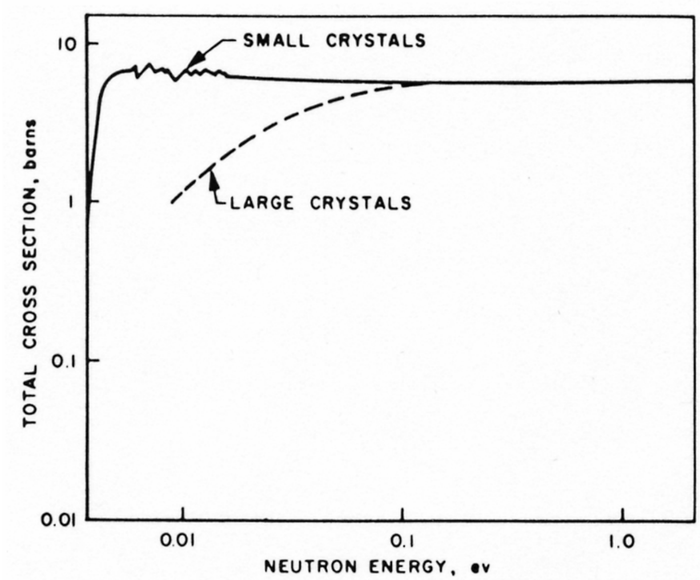

Fig. II-4-1 Total neutron cross-section as a function of neutron energy of fine-grained and coarse-grained beryllium. The coarse grains were obtained by heat treatment.[19]

II-5—Miscellaneous Properties

Properties that were not presented in the previous sections are listed in Table II-5-1.

Table II-5-1 Room-Temperature Values of Miscellaneous Properties of Beryllium.[1-4]

Sonic velocity	12,588m/s
Optical reflectivity (white light)	50 to 55%
Ultraviolet reflectivity	50%
Infrared reflectivity (10.6 μm)	98%
Solar absorptivity (polished plate surface)	46%
Electrical conductivity	40.7% of IACS (0.24mho/cm)
Electrical resistivity (25°C)	$3.70 \times 10^{-8}\Omega$-m ($4.31 \times 10^{-8}\Omega$-m)
Magnetic susceptibility, χ_{mass} (20°C)	-1.00×10^{-6} cm^3/g (diamagnetic)
Photoelectric work function	3.92 eV
Electron work function (polycrystal)	4.98 eV (depends on surface cleanliness
Ionization potential for neutral atom	9.3227 eV
Electron-binding energy for Is (K) level	111.5 eV

The electrical resistance of beryllium as a function of temperature from room temperature to 1080°C is shown in Fig. II-5-1.[13] A similar plot is shown in Fig. II-5-2.[7] The data in the two figures are similar at the lower temperatures but differ at the higher temperatures, for example, these values at 800°C are about 26 and 31 microhom centimeters in Figs II-5-1 and II-5-2, respectively, The author[7] states that the electrical conductivity (or resistivity) varies considerably with purity and method of fabrication (as is generally the case for essentially all metals and their alloys). He also states that the conductivity values for beryllium range from 35 to 42% of the IACS values. Figure II-5-3 shows a significant spread in resistivity values of beryllium having various densities (1.823 to 1.865 g/cm^3), impurity level, and processing levels.[22]

Table II-5-2 lists the electrical resistivities of polycrystalline beryllium over a range of temperatures from –263 to 673°C (10 to 900 K). Electrical resistivity measurements were reported on 4-mm beryllium rods, grades CR and CS (French). Billets were extruded into rods in the temperature range between 1000 and 1050°C and then annealed at 800°C producing a recrystallized structure with polygonization (substructure within the grains). The extruded rods had similar textures that were not “appreciably altered” by the anneal. Both as-swaged and swaged-and-annealed rods were evaluated at four temperatures. The results are shown in Table II-5-3.[32] The author points out that the resistivity varies considerably with metallic impurity, and, the lower the temperature the greater is this variation.

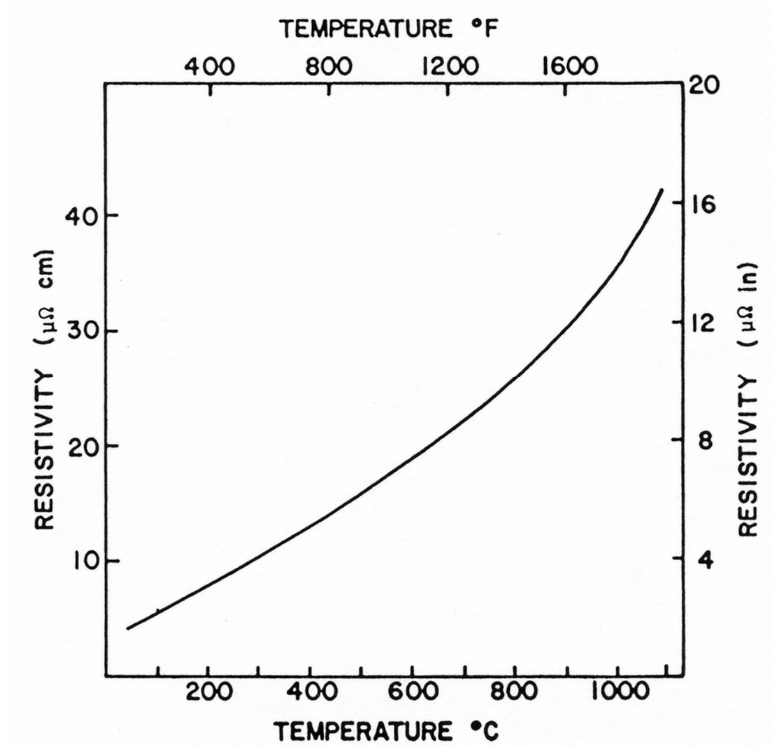

Fig. II-5-1 Electrical resistivity as a function of temperature of normal-purity beryllium block.[13]

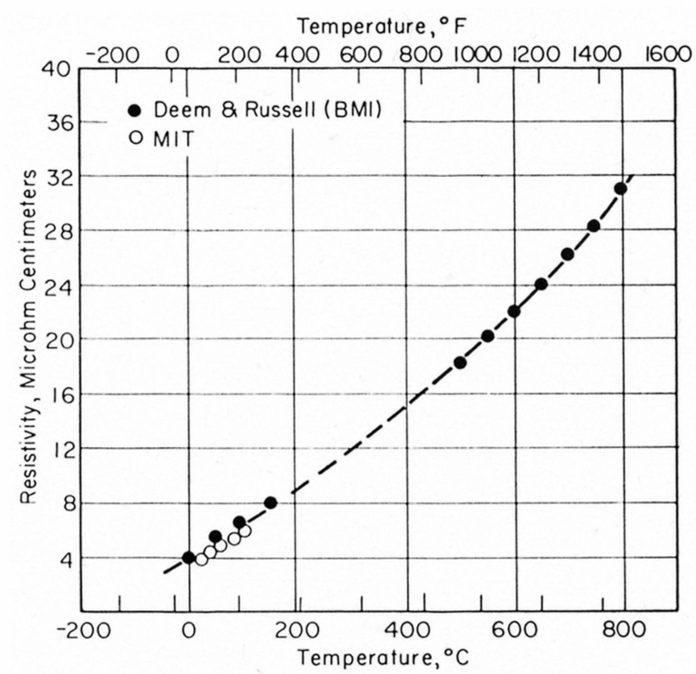

Fig. II-5-2 Effect of temperature on the resistivity of beryllium for two investigations.[7]

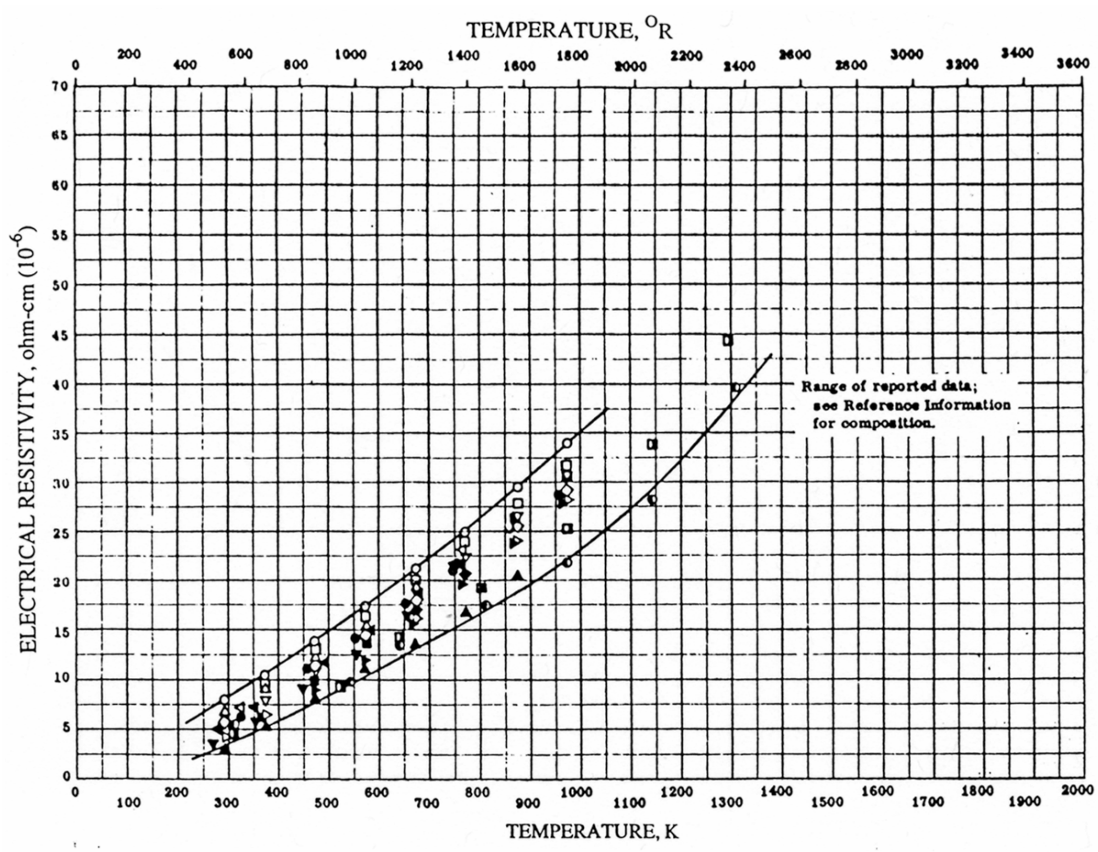

Fig. II-5-3 Electrical resistivity as a function of temperature of beryllium having various densities (1.823 to 1.865 g/cc), impurity levels, and processing histories.[22]

Table II-5-2 Electrical Resistivity of Polycrystalline Beryllium[6]											
T, K	10^{-8} Ωm	T, K	10^{-8} Ωm	T, K	10^{-8} Ωm	T, K	10^{-8} Ωm	T, K	10^{-8} Ωm	T, K	10^{-8} Ωm
10	0.0332	60	0.067	150	0.510	293	3.56	400	6.76	700	16.5
20	0.0336	80	0.075	200	1.29	298	3.70	500	9.9	800	20.0
40	0.0367	100	0.133	273	3.02	300	3.76	600	13.2	900	23.7

Table II-5-3 Electrical Resistivity of Beryllium Rods at Different Temperatures.[32]									
Rod history	Rod No.	Grade	BeO, %	Total metallic impurities	Grain size, μm	Resistivity, microhm-cm			
						273°K	77.4°K	20.3°K	4.2°K
As-extruded	1	CR	0.9	0.18	10-80	3.92	1.09	1.03	1.03
	2	CR	1.2	0.10	10-80	3.49	0.65	0.61	0.61
	3	CR	0.1	0.08	30-200	3.28	0,55	0.51	0.51
	4	SR	0.2	0.02	30-200	2.79	0.066	0.037	0.037
Extruded and annealed	1	CR	0.9	0.18	10-80	3.72	0.96	0.88	0.88
	2	CR	1.2	0.10	10-80	3.17	0.41	0.37	0.37
	3	CR	0.1	0.08	30-200	3.15	0.50	0.45	0.45
	4	SR	0.2	0.02	30-200	2.85	0.063	0.37	0.37

The electrical resistivity at room temperature and at 4.2 K and the residual resistance ratios[f] for various purity levels of beryllium are listed in Table II-5-4. The purity level appears to have an appreciate affect on the resistance at 4.2 K, while only a minor affect at room temperature. Significant effects are seen for the relative resistance ratios [$\Omega_{RT}/\Omega_{4.2\ (K)}$].[2] Different processing histories are also indicated in Table II-5-4

Table. II-5-4 Electrical Resistivity and Residual Resistance Ratios (Relative Resistance) for Various Purity Levels of Beryllium.[2]			
Specimen history	Resistivity, μΩ-cm, Room Temp.	Resistivity, μΩ-cm, 4.2 K	Relative resistance, $\Omega_{RT}/\Omega_{4.2\ K}$
Commercial purity, rolled sheet, longitude	5.350	1.068	5.01
Commercial purity, rolled sheet, transverse	4.864	0.967	5.03
Commercial purity, hot pressed	5.543	1.167	4.75
Intermediate purity, hot pressed	4.706	0.394	11.94
High purity Pechiney SR, hot pressed	4.266	0.027	158
Vacuum-melted Pechiney flake, single distilled	——	——	80 to 750
Vacuum-melted Pechiney flake, double distilled	——	——	200 to 900

[f] The residual resistance ratio is the ratio of the resistance at room temperature to that at 4.2 K.

The electrical resistance as a function of pressure relative to the resistance at 10 GPa and 25°C is shown in Fig. II-5-4.[33]

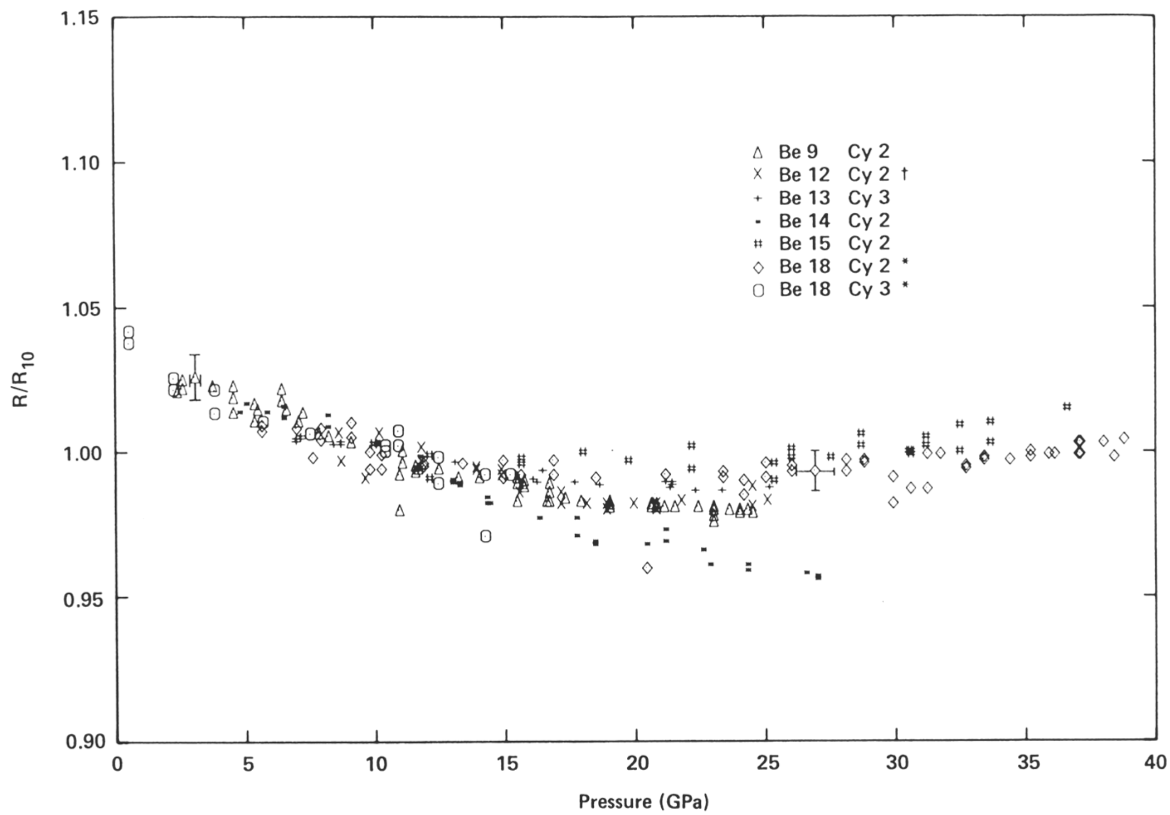

Fig. II-5-4 Residual (relative) resistance, R/R_{10}, of beryllium as a function of pressure taken during the second or third cycle (as indicated) while increasing pressure.[33]

The thermo-electric power of hot-pressed beryllium relative to copper as a function of temperature at low temperatures is shown in Fig. II-5-5. Curves for both parallel and perpendicular to the pressing direction are presented.[2] The thermo-electric power of beryllium against platinum is given as 1.6 and 2.6 μV/°C for 99.96 and 99.78% purity, respectively. A straight-line increase from 8.2 μV/°C at 336°C to18 μV/°C at 800°C is reported for beryllium against platinum as shown in Fig. II-5-6.[2, 7]

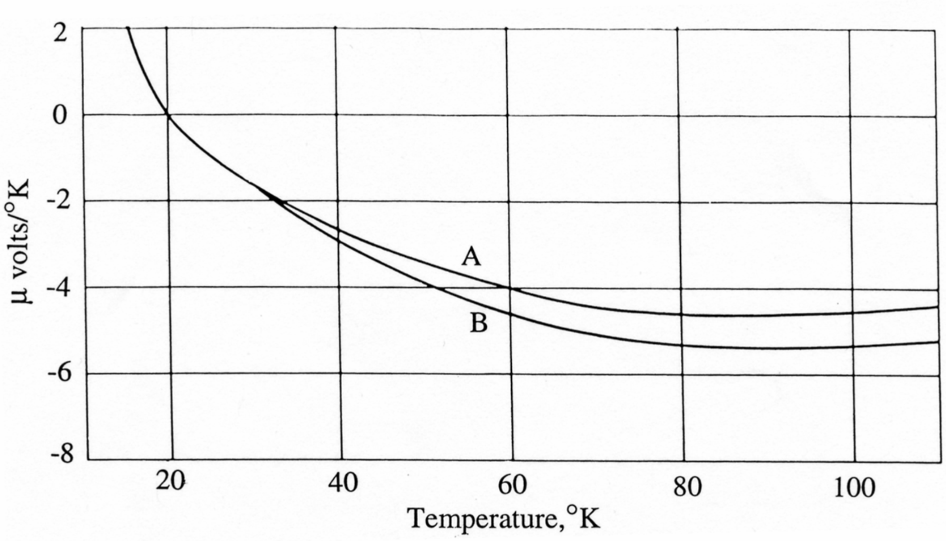

Fig. II-5-5 The thermo-electric power of hot-pressed beryllium against copper: A—specimen axis parallel to pressing direction, B—specimen axis perpendicular to pressing direction.[2]

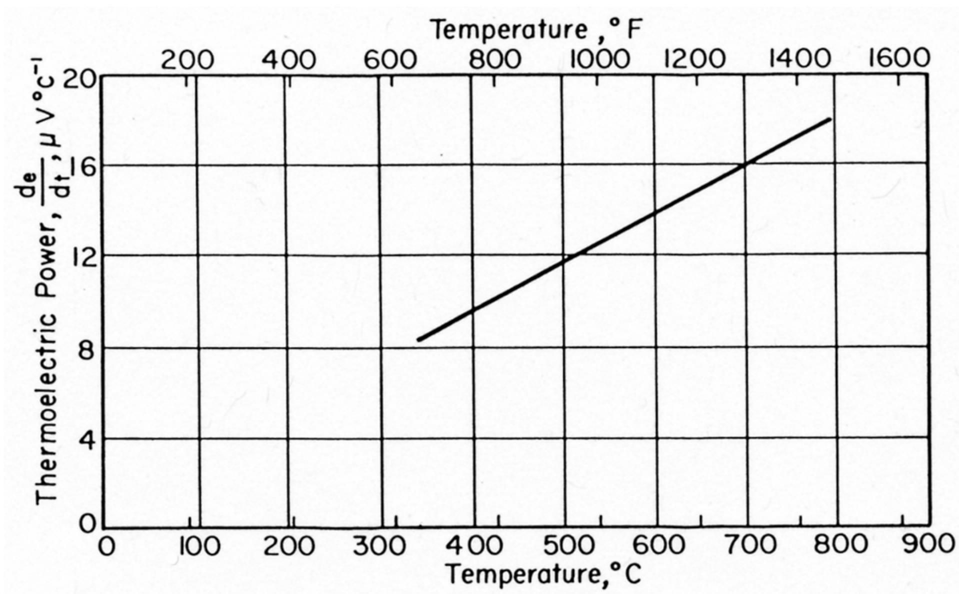

Fig. II-5-6 Thermoelectric power of beryllium against platinum as a function of temperature.[7]

The normal spectral reflectance at a series of wave lengths of anodized beryllium anodized by two different methods are listed in Table II-5-5.[2] Figure II-5-7 is a plot of normal spectral reflectance of beryllium as a function of wave length using 0.625-mm-thick samples.[22] The data reflects the use of three different hohlraum (target chamber) temperatures (523, 773, and 1273 K).

Table II-5-5 Normal Spectral Reflectance of Anodized Beryllium at a Series of Temperatures.[2]		
Wavelength, μm	Anodized in chromic acid	Anodized in sodium hydroxide
0.4	0.172	0.075
0.6	0.179	0.052
0.8	0.168	0.058
1.0	0.165	0.68
2.0	0.280	0.203
4.0	0.355	0.286
6.0	0.335	0.514
8.0	0.317	0.772
10	0.560	0.773
15	0.673	0.606
20	0.494	0.899

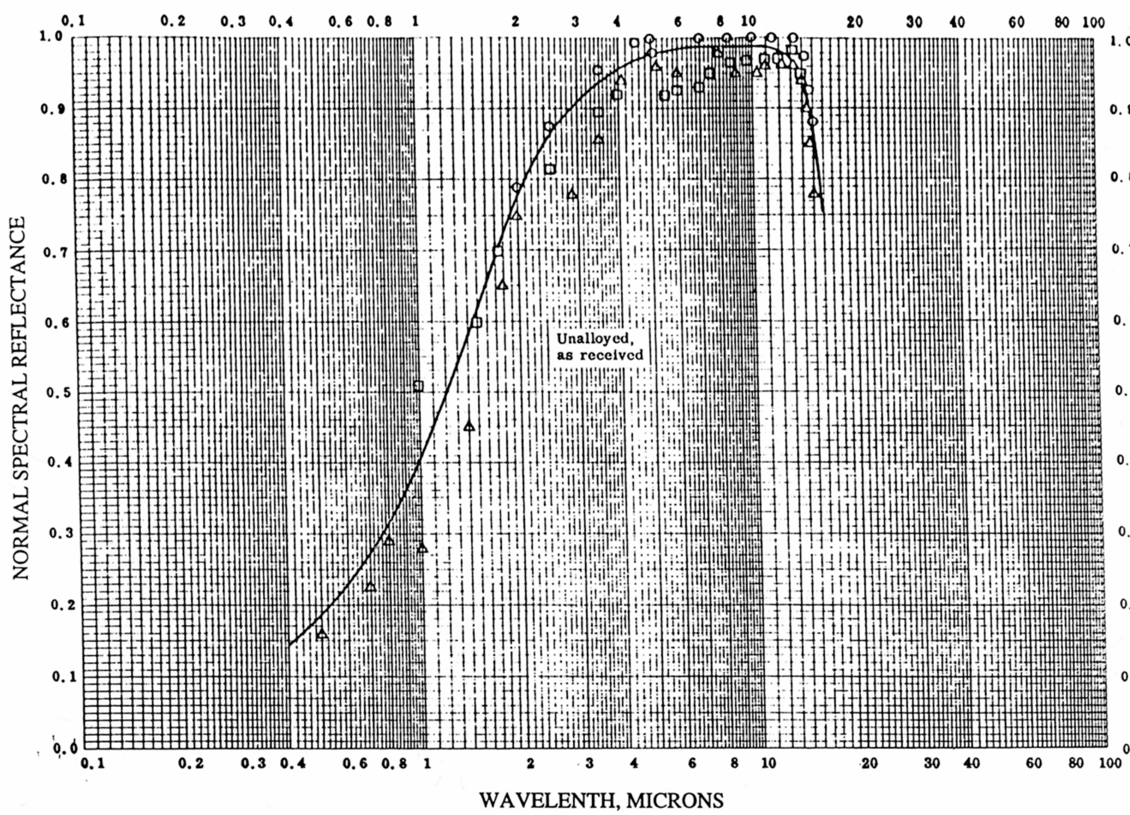

Fig. II-5-7 Normal spectral reflectance of as-re□ived, washed, unalloyed,0.635 mm-thick beryllium as a function of wave length :O—hohlraum (h) at 523 K, measuring temperature (mt) < 322 K, wavelength range (wr) 2.00 to 15.00 μm; —h at 773 K, mt < 322 K, wr 1.00 to 14.00 μm; Δ—h at 1273 K, mt < 322 K, wr 0.50 to 15.00 μm.[22]

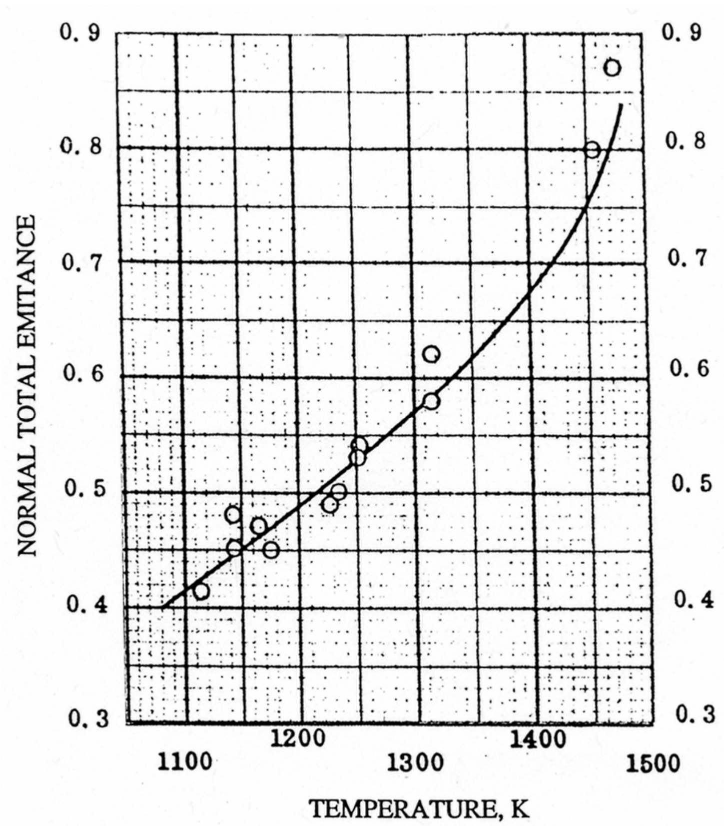

Fig. II-5-8 Normal total emittance of beryllium in air as a function of temperature.[22]

The normal total emittance of beryllium in air as a function of temperature is shown in Fig. II-5-8.[22] The composition and history of the metal were not given. Figure. II-5-9 shows the normal spectral transmittance of beryllium as a function of wavelength at 298 K.[33] Measurements were made on aluminum-backed beryllium film (875 ± 100 Å thick) with both aluminum and beryllium being deposited by evaporation on a glass side. The data was corrected for transmittance of aluminum and glass. About 10% error was indicated for $\lambda > 0.035$ μ and 25% for $\lambda < 0.035$ μ. Geometries of θ and were approximately zero. Figure II-5-10 shows the normal total emittance as a function of temperature during heating (1116 to 1473 K) and cooling (1473 to 1255 K). The geometry was given as θ[1] being approximately zero.[22]

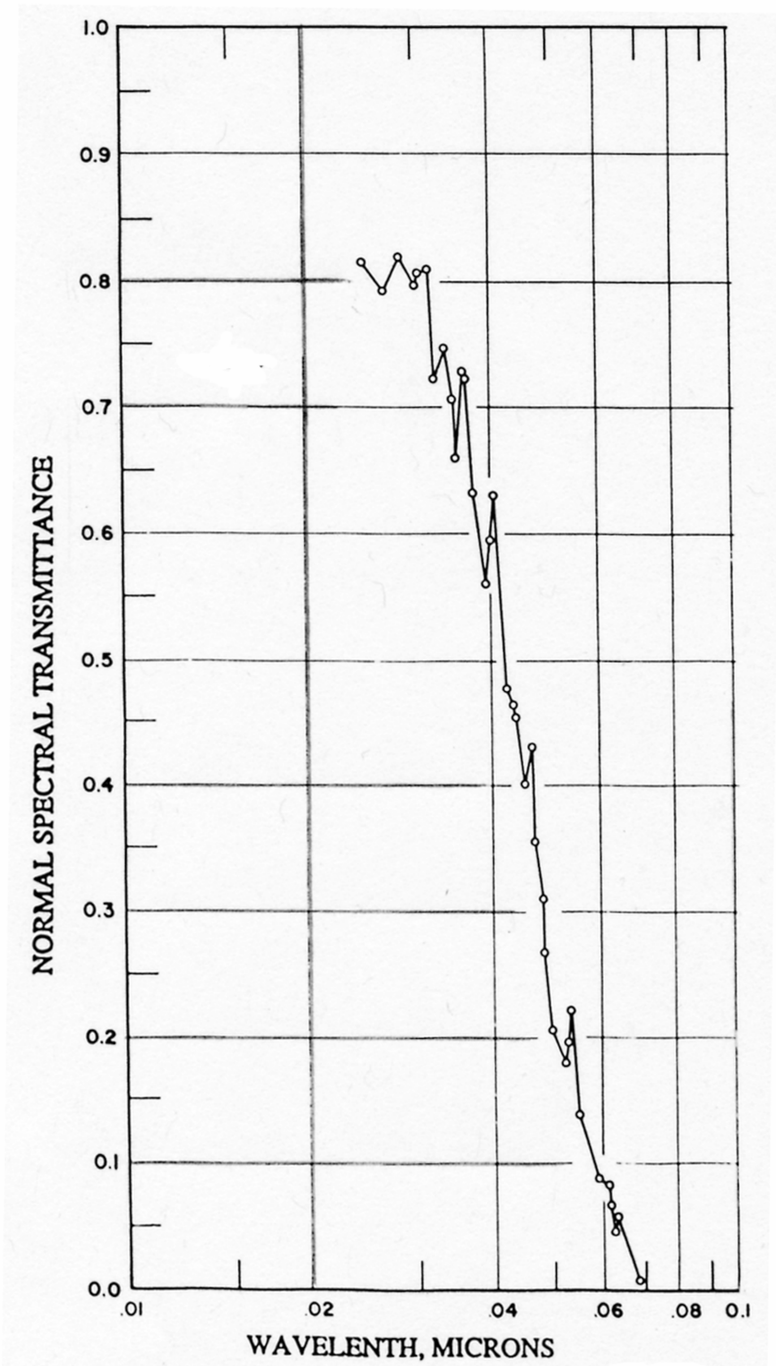

Fig. II-5-9 Normal Spectral Transmittance of beryllium as a function of wave length at 298 K measured on an aluminum-backed beryllium film (875 ± 100 Å thick). Aluminum and beryllium, evaporated at 2 x 10^{-5} torr on a glass slide. Data corrected for transmittance of Aluminum and glass. About10% error for $\lambda > 0.035$ µm and < 25% for $\lambda < 0.035$ µm. Geometry, θ and $\theta^1 \sim 0$. [34]

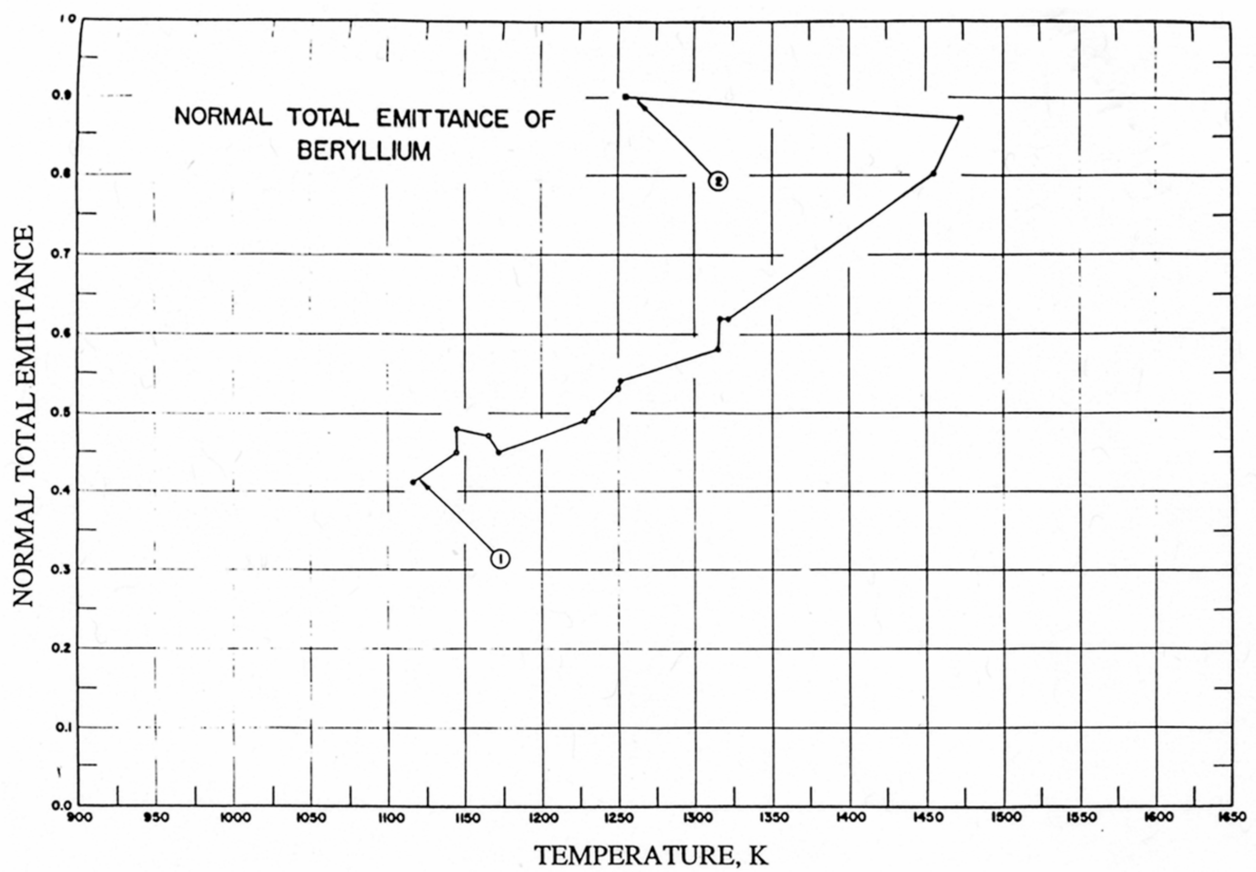

Fig. II-5-10 Normal total emittance of beryllium as a function of temperature: 1—heating (1116 to 1473 K); 2—cooling (1473 to 1255 K); geometry, $\theta^1 \sim 0$.[22]

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